Integration in Science Education: Trans-disciplinary Inquiry and Conceptual Infrastructures

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Educational circles take it for granted that science education should help learners achieve an integrated understanding of information (data points) within a field of study. Such integration calls for the specification of correlational and causal generalizations in the curriculum, which are then integrated through scientific theories. Less recognized, perhaps, is the need for integration across fields: trans-disciplinary integration. This paper attempts to make a case for trans-disciplinary integration along the dimensions of ontology and epistemology, and provides an illustrative sample of a high school curriculum (specification of desired learning outcomes) along both these dimensions.

Integration by the Human Brain and Science

The human brain has an extraordinary capacity to convert sensory and non-sensory stimuli, or ‘data points’, into sensations and sense perceptions, and integrate those experience-fragments into structures that we call ‘knowledge’ of the external world. It is these structures that allow us to make sense of our experience; and they guide our choices of action. A great deal of such integrative construction of knowledge takes place below the level of consciousness. The ‘data’ recorded by the retina, a biological instrument, for instance, are automatically integrated, and interpreted as objects in the external world.

Scientific inquiry can be thought of as a self-conscious and systematic extension of the brain’s predisposition for such integration, taking place at the levels of both the individual scientist and the scientific community.

If I had to pick one single goal of science education as the one with greatest value for all students (whether future scientists, science professionals, or individuals who may not need any specialized scientific knowledge in their professional lives), it would be the ability to engage in the modes of integration that are characteristic of scientific inquiry.

In what follows, I explore four levels of such integration: descriptive-phenomenological, explanatory-theoretical, ontological, and epistemological. A framework of this kind, I believe, has the potential to meaningfully guide decisions on science curricula, classroom activities, learning materials, and assessment tasks.

Integrating Experience-Fragments (Descriptive-Phenomenological)

An experience that human beings everywhere and through all times integrate is the following observational generalization about day and night:

\[ \text{Night follows day and day follows night.} \]

This generalization does not require any conscious or systematic observation, let alone scientific inquiry. But it integrates as part of our commonsense knowledge the data points that are fragments of our experience of day and of night. For people living near the equator, day and night are approximately equally divided, so that each data point has the same duration. For observers away from the equator, such data points would involve unequal durations of day and night. A careful documentation of these data points reveals the following observational generalizations:

\[ \text{The total duration of each day-night pair is constant.} \]

\[ \text{There is a stretch of time in which the relative duration of nights increases (the duration of days decreasing correspondingly), followed by a stretch of time in which it gradually decreases (the duration of days increasing), completing a cycle in 365 day-night pairs.} \]

Each of the three observational generalizations above connects and integrates three different collections of data ‘fragments’ into a pattern. They are accompanied by further integration of experience fragments such as the following:
The locations of sunrise and sunset for each day-night pair shift from north to south and back, completing a cycle in 365 day-night pairs.

The (mean) temperature during the day-night pairs gradually increases and then gradually decreases, completing a cycle in 365 day-night pairs.

These generalizations integrate experiences of phenomena on earth. Of these, the experiences of sunrise and sunset are associated with an entity in the sky that we call the sun.

Turning our attention to experiences of phenomena in the sky, we see a set of shining dots in the night sky that we call stars or planets, and a shining circular disc that we call the moon. At the phenomenological or descriptive level, the observational regularities in these night sky dots can be stated as follows:

The relative positions of the bright dots in the night sky (which we call 'stars') do not change with respect to one another. The positions do change in the case a handful of dots (which we call 'planets').

In relation to the earth, the overall orientation of the dot configuration undergoes a continuous change through each night; this can be described as a movement of the dots along a circular arc around a central dot (which we call a 'pole star').

If we take the configuration of 'stars' as our reference point, the 'planets' appear to move in a given direction for several days at a stretch, then reverse direction (called 'retrograde motion') and then go back to the original direction.

These observational generalizations can be thought of as observational/phenomenological laws. In stating these laws, we are expressing the regularities as we experience them, without making any claims about the deeper reality that underlies these experiences.

The very first step in learning science is to develop the capacity to notice such regularities in our experience of nature, to formulate them clearly and explicitly, and to make systematic observations to test them, such that they are validated as correct, or rejected as flawed. This is the essence of observational science (including experimental science).

Integrating Observational Generalizations (Explanatory-Theoretical)

Our observational laws integrate fragments of our experience. But they do not help us understand the external reality that underlies our experience. Is it simply chance that the same number, 365, appears in three different observed cycles? It is logically possible that one cycle is 365, another is 400, and yet another 52. Is there a deeper reason for why they coincide? Also, why do the relative durations of day and night vary more and more as we move away from the equator? Could it have been the other way round? And given the variation in the relative durations of day and night, why is the duration of the day-night cycle a constant?

Likewise, we notice two further cycles of apparent movement: those of the sun from east to west in the day, and the stars around the pole star at night. Why do these two cycles coincide? Could it have been different, say, the sun cycle being twice the duration, or half the duration, of the star cycle? Could the cycles have been entirely uncorrelated?

Such questions demand that we approach these phenomena as clues to something deeper, and search for that deeper reality. Take, for instance, the ‘bright dots’ in the night sky. At the deeper level, we can interpret the bright dots in at least two ways. One is as bright objects against a dark background, like fireflies in a dark room. The other is as holes in a dark screen, say, in front of a celestial brightness, like holes in a black umbrella opened on a sunny day.

Having chosen how to represent our perceptual experiences in terms of such deeper entities, we also have to choose how to represent relations and processes. We may, for instance, interpret the perceived movement of the dots as resulting from the celestial entities moving around a stationary earth, as the earth moving around stationary celestial entities, or as some combination of the two. Conceptualizing perceptual experiences in terms of such entities, relations, and processes is the beginning of theoretical integration. To use Plato’s metaphor of caves, what we perceive through our senses or instruments are shadows; from these shadows, we must make inferences about a reality that is not accessible to direction perception.

Our observational generalizations integrate data points in our experience of phenomena. The next step in scientific inquiry is to integrate our generalizations as entities, relations, and processes of a reality underlying the phenomena, through explanations. The heliocentric theory of the solar system, and Kepler’s laws of planetary motion within that theory are classic example of such integration of observational generalizations.
In a completely different domain of data points, we have Galileo’s integration of the observational laws governing the simple pendulum on the one hand and falling bodies on the other. We also have Newton’s theoretical integration of gravity and motion in terms of the concept of gravitational force, unifying the observational laws governing the apparent motion of heavenly bodies (Kepler) and the motion of bodies on earth (Galileo).

Likewise, the data points integrated by the theories of magnetism, electricity, and optics exhibit unexpected family resemblances. Such family resemblances call for an explanation. Maxwell’s laws of electromagnetism provide a unified explanation for these apparently unrelated experiential phenomena, achieving the integration of the laws in the three domains.

Before proceeding, let me remark that science education has the responsibility to help students develop the capacity for such theoretical integration. This cannot happen without providing space in the curriculum for deep reflection, contemplation, imagination, and rigorous reasoning, along with some mathematical modeling and mathematical calculations.

**Integrating Scientific Theories: Trans-Disciplinary Ontology**

Beyond theoretical integration lies a more abstract level of integration, that of theoretical concepts and propositions that cut across disciplinary boundaries (as well as across discipline-internal boundaries between sub-disciplines). Such trans-disciplinary concepts and propositions enter into the very development of theories in particular disciplines, connecting and integrating what would otherwise remain fragmented. These concepts and propositions do not directly yield theories that predict data points or even observational generalizations. But they provide the infrastructure that guides our observations and shapes the theories that explain them. They form a trans-disciplinary ontology that constitutes an infrastructure on which scientific knowledge and inquiry are built.

For instance, consider the following concepts that we are all familiar with the following: system, structure, function, organization, unit, atomic unit, dynamical system, complex system, complex adaptive system, set, population, category, regularity, probability, randomness, correlation, causation, trait, variable, variation, invariance and variability, change, origin, evolution, development, history…

The scope of the concepts of atom and electron is restricted to physics, but the scope of the concepts of unit and atomic unit extend to most scientific disciplines. The origin of life and the evolution of biological species are part of biology, but the concepts of origin and evolution cut across disciplinary boundaries (origin and evolution of the universe, origin and evolution of the solar system, origin and evolution of the earth, origin and evolution of human language, origin and evolution of capitalism…). These are what we mean by trans-disciplinary concepts.

Why should we be concerned with trans-disciplinary concepts? Because they constitute the foundations for discipline-specific knowledge and inquiry. Take, for instance, the terms ‘system’, ‘structure’, and ‘function’ that students are exposed to in biological, mental, and societal sciences. System and structure appear in the physical sciences as well. What concepts do these terms refer to? Suppose we define them as follows:

- **An organization** is an entity that has a structure, system(s) and function(s).
- **A structure** is a set of entities interconnected through part-whole relations, supplemented by other relations such as ordering, dependence, and correspondence.
- **A system** is a set of interacting entities, typically performing a set of functions.
- **The function** of a system or structure is what it does in its environment.

Given these definitions, it follows that a trans-disciplinary theory of organization would include trans-disciplinary theories of structure, system, and function. An organization in this sense could be a business organization, an educational organization, a government organization, an organism, an organ within an organism, an individual, a group, a community, a society, a neighborhood, a country, a continent, a planet, a galaxy, a universe, and so on.

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1 This remark warrants three brief notes on the use of the terms physical, biological, mental, and societal. First, if the term ‘physical sciences’ refers to a cluster of scientific disciplines dealing with physical phenomena (astronomy, physics, chemistry, earth sciences…), there is no reason why the corresponding term ‘biological sciences’ should not refer to a cluster of scientific disciplines that deal with the phenomena of life. ‘Biology’, then, is not a single discipline. Second, by the same token, the term ‘mental sciences’ should include the study of not only the human mind (psychology), but also the chimpanzee mind, the drosophila mind, and so on. The term ‘societal sciences’ should include the study not only of human societies, but also of chimpanzee, bird, ant, and bacterial societies. This means that the current fragmentation of the study of brain-mind-society-behavior into ‘biology’ on the one hand, and ‘social sciences’ on the other, cannot be maintained. We might, of course, view ‘human sciences’ as a specialization that cuts across biological, mental, and societal sciences, exploring the question what makes us human. Third, engineering, technology, and medicine would then come under applied sciences within the physical, biological, mental, and societal sciences.
a cell, a sculpture piece, a poem, or a motorcycle. In contrast, galaxies, star-planet systems, crystals, molecules,
and atoms may not have the dimension that we recognize as function, in which case we would not treat them as
organizations.

Trans-disciplinary theories of systems already exist. Bertalanffy’s General Systems theory, the theory of
dynamical systems (e.g., clock work systems, cybernetic systems), Complex Adaptive Systems (learning and
evolving systems), and the like are attempts to study the nature of systems. What science needs next are theories
of structure and function, and a general theory of organization that includes all these.

To take a more specific example of trans-disciplinary ontology, and connect it to discipline-specific concepts,
consider the study of skin in biology. The skin is composed of layers of cells that cover a large mass of cells in a
multi-cellular organism. It is also a sense organ. If we compare the skin with geopolitical borders demarcated by
lines in a world map, we see that they are very different entities whose studies belong to completely different
disciplines, namely, multi-cellular biology and geopolitics. But suppose we shift our perspective and view skin
and national borders as equivalent. Suppose we say that skin and national borders are both boundaries, and the
object of our study is boundaries. The obvious question then is, “What is ‘boundary’ such that skin and national
borders are both boundaries?” When we pursue this question, it becomes obvious that there are other entities that
are instantiations of boundaries, for instance, cellular membranes, fences, and walls.

If we treat skin, national border, cell membrane, fence, and wall as unrelated entities, we would define each
concept to suit discipline-specific purposes, and pursue research that does not require biologists, political
scientists, and architects to collaborate, or to understand each other. In contrast, studying the shared
characteristics of boundaries requires trans-disciplinary perception and thinking, and would result in integration
across disciplinary boundaries.

If we contemplate what is shared across the cell membrane, skin, wall, fence, and national border, what emerges
is a view of ‘boundary’ as a mechanism to separate members of a set from non-members, keep the members
connected together and provide unity. If we take this function as a defining feature of ‘boundary’, then the socio-
cultural perceptions of us-and-them are also results of boundaries, and in turn, result in boundaries.

Now, consider an assertion like the following: The us-and-them attitudes of human communities are also found
in non-human animals, and even in bacteria and immune cells; it is a manifestation of the same concept of
boundary that is seen in national borders, skin, and cell membrane. This statement may not make much sense
from within a discipline-internal perspective. But a trans-disciplinary perspective would allow us to see both
what is shared across the different instantiations of the concept, as well as what is significantly distinctive about
each of them, and provide the foundations for a general theory of boundaries.

Likewise, a trans-disciplinary perspective allows us to see the unity of the concepts of mind and consciousness
currently fragmented as:

• human mind and consciousness, studied as ‘psychology’ within ‘social sciences’, and
• animal mind and consciousness, studied as ‘biology’ within ‘natural sciences’.

Similarly, a trans-disciplinary perspective allows us to see the unity of human society studied under sociology,
and animal society studied under biology.

Let me turn to a different domain. The terms point, line, dimension, and space conjure up the world of Euclidean
geometry. If we are locked into this world, it would be hard to understand how a line drawn on the surface of a
sphere can be a straight line. But if we move to a higher level of abstraction and define a line-segment as the
shortest path between two points, we can visualize straight lines not only on flat surfaces but also on curved
surfaces.

Abstracting further, consider the concepts of ‘point’, ‘line’, ‘dimension’, and ‘space’ in geometry and statistics.
In geometry, we can say either that a line is composed of points or that a point is an intersection between two (or
more) lines. The three vertices of a triangle then are points in a two-dimensional Euclidean or Riemannian space.
In statistics, a ‘data point’ is a set of attributes of an entity along relevant parameters. The statement that Zeno is
five feet seven inches tall, weighs 50 pounds, is a Martian, is male, and is 98 years old becomes a (data) point in
a five-dimensional space. If so, the statement that there is a correlation between height and age in the human
population becomes a statement about a line in a two dimensional space of height and age. A correlation in
statistics, in other words, is the analogue of a line in geometry. Once we perceive such equivalences/analogues,
the more abstract concepts of point, line, dimension, and space become trans-disciplinary concepts, transcending
geometry and statistics.

Consider two squares of length 5 cm. The relation between them is that of congruence. The relation between two
congruent shapes on a two dimensional flat surface is captured in terms of the transformations of translation,
rotation, and reflection. Now consider a 5 cm square and an 8 cm square. The relation between them is that of the mathematical concept of similarity, captured in terms of the transformation of enlargement/reduction. Now consider a parallelogram, a rectangle, and a square. They are all quadrilaterals, related through the transformations of shearing or compression. A triangle, a quadrilateral, a pentagon, and a hexagon are all polygons. A polygon and an ellipse (including a circle) are both closed shapes. In terms of rubber sheet topology, a polygon and an ellipse are invariant under the transformation of deformation. A mug and a doughnut also count as the ‘same’ object because they are invariant under deformation. The kind of thinking we are pursuing in exploring such analogues and abstractions is the geometry-internal equivalent of trans-disciplinary thinking.

From a trans-disciplinary perspective, what we call homology, analogy, homomorphism, polymorphism, allomorphy, and alleles are the same — in the sense that I am the same person today that I was two weeks ago, and in the sense that a face viewed from two different angles is the same face, without claiming identity. The essential structure of analogy in these concepts also manifests itself in the concept of variations of the same theme: transformation and symmetry in mathematics, archetypes in Jungian psychology, leitmotif in music, and metaphors in poetry.

Trans-disciplinarity, in other words, is itself a manifestation of the creative and integrative faculty of the human mind: a combination of the power of analogical thinking and abstraction. It allows us to make connections across apparently different or even unrelated entities and processes, integrate them, and see unity in apparent diversity, facilitating creativity and cross-pollination. This is what the English poet Coleridge called esemplastic imagination, “bringing together or able to bring together different concepts and thoughts into a unified whole: the esemplastic ability of the imagination.” (http://www.yourdictionary.com/esemplastic)

Accepting trans-disciplinary ontology as a valuable foundation for building discipline-specific knowledge, and trans-disciplinary perception and thinking as valuable goals of science education, implies two commitments on the part of science educators. One is to jointly develop a trans-disciplinary infrastructure such that discipline-specific concepts, where relevant, can find a place as special instances of the concepts of trans-disciplinary ontology. The other is to nurture the capacity for the mode of analogy-based abstraction.

Integrating Ways of Knowing: Trans-disciplinary Epistemology

In the above section, we looked at the trans-disciplinary conceptual structures that underlie our knowledge of the world: the entities, sets, processes, relations, correlations, causes, structures, systems, and so on that inhabit it. Parallel to these ontological concepts are a set of trans-disciplinary epistemological concepts that underlie our shared ways of knowing: abstract concepts about how we investigate the world, not what exists in the world per se.

Students of all academic disciplines are exposed to the concepts of theories and interpretations, and to the concept of justification under the terminology of proof, argumentation, or evidence. Students of all science disciplines are exposed, in addition, to the concepts of definitions, laws, hypotheses, experiments, observations, and calculations. Of these concepts, definitions are relevant for students of mathematics and analytic philosophy as well. Students specializing in mathematics are exposed also to the concepts of conjectures, theorems, axioms, and lemmas.

The justification of mathematical conclusions is called a proof, while its counterpart in science is evidence. A closer look at the concept of justification reveals a structure of grounds, reasoning, and conclusions. In mathematical inquiry, the propositions we wish to justify (knowledge claims) are conjectures, and once justified, they become theorems. Their counterparts in scientific inquiry are hypotheses and theoretical proposals. The grounds for justification in scientific inquiry are data (points) or observations; in mathematical inquiry they are axioms, definitions and previously established theorems. The mode of reasoning used for the justification in mathematical inquiry is that of classical deduction. Scientific inquiry allows for a wider range of reasoning, including probabilistic deduction, defeasible deduction, induction, abduction and speculative deduction.

These are some of the concepts of the infrastructure of epistemic concepts that underlie scientific and mathematical inquiries. Typically, these foundational concepts are not part of curricula at any level, and their understanding is not tested in any examination. I would like to suggest that a curriculum that aims at the integration not only of knowledge but also of inquiry take these epistemic concepts seriously in the design of curricula, learning materials, classroom activities, and assessment.

Why should we include inquiry in curricula? Because it is valuable in itself, and is the foundation for research. That it is important for graduate students to acquire the ability to engage in independent research is widely accepted in most parts of the world. More recently, there is also awareness among researchers, educators, and
educationists that research abilities are crucial right from the undergraduate level, and perhaps even among high school students.

While this awareness is indeed welcome, several questions arise in providing ‘research training’ to high school and college students:

- Only very few high school and college students go on to become professional researchers. For those who don’t, what would be the value of learning research skills?
- Research demands that its outcome be a contribution to the collective pool of knowledge. What are the chances of high school and college students making an original contribution without mastering the state-of-the-art knowledge of the field?
- How can high school and college teachers, mostly not researchers themselves, teach students how to do research?

Perhaps it would be useful to re-evaluate the idea of teaching research skills at high school and college. What is worthwhile in this enterprise is the goal of helping high school and college students to develop the capacity to think and inquire like a mathematician, a theoretical scientist, an experimental scientist, or a philosopher. I would like to suggest that what we should aim at in school and college education is not discipline-specific specialized research skills, but the broad spectrum of inquiry abilities that cut across disciplinary boundaries. These would then serve as the foundations for future research, while being of value to all those who choose not to follow the path of academic research as a profession.

How to extract the DNA strands from a bunch of cells, how to operate the X-ray crystallography machine, how to use a sound spectroscope, how to design an fMRI experiment, etc., are highly specialized research skills that are hardly necessary for the majority of students who graduate from high school or college. However, how to gather, process, and interpret quantitative data, how to look for an answer to a question, how to design an experiment to test a hypothesis, how to justify or refute a claim, how to critically evaluate a conclusion and the justification that supports a conclusion, how to construct and evaluate a theory or theoretical interpretation, and so on, are important inquiry abilities that are valuable to all high school and college students regardless of their specialization.

In other words, what I am suggesting is that it is important for all high school and college students to develop not only an appreciation of the ways of knowing that result in academic knowledge, but also a rudimentary capacity to engage in those ways of knowing, in an integrated trans-disciplinary manner. Integration comes not only in the understanding of scientific (and other) epistemologies, but also in their practice. The understanding, abilities, habits of thought, and mindset that result from such an education would act as the foundations for thinking and inquiry in (a) research, (b) professional spheres, and (c) enlightened and responsible citizenry needed for participation in democratic processes in public spheres.

Integrated Inquiry-Oriented Science Education: A Tentative Curriculum

If we were to accept the broad thrust, if not the details, of the preceding sections, what would the implications be for curricula, learning materials, classroom activities, and assessment tasks? I give below is what might be viewed as a (tentative/incomplete/initial) structured checklist to consider for the design of a science curriculum that pays attention not only to the understanding of scientific knowledge but also to the abilities and habits of scientific inquiry, and from not only a discipline-internal perspective but also a trans-disciplinary one.

Understanding of

- discipline-specific knowledge concepts and knowledge propositions;
- justification (evidence/arguments) for or against these concepts and propositions;
- trans-disciplinary concepts that constitute the infrastructure of knowledge; and
- trans-disciplinary concepts that constitute the infrastructure of inquiry.

Ability to

- apply the discipline specific knowledge concepts to particular problems and situations;
- engage in trans-disciplinary inquiry, drawing on the trans-disciplinary concepts; and
- engage in discipline-specific inquiry and research, drawing on the capacity for trans-disciplinary inquiry-ontology-epistemology as the foundation.

Components of the capacity to engage in trans-disciplinary inquiry would include:

Observational science: ability to
• observe/perceive what an untrained mind may not; notice interesting patterns in what one observes/perceives; formulate observational conjectures on the basis of preliminary observations;
• come up with designs to gather systematic evidence/data to test correlational and causal conjectures; execute the designs; gather and process data; and arrive at conclusions on the correctness of the conjectures.

Theoretical science: ability to
• identify correlational/causal generalizations that call for theoretical explanations; arrive at theoretical explanations; formulate the propositions of a theory with clarity and precision; deduce the predictions of the theory; design observational/experimental schemes to test the predictions;
• check for logical consistency within and across theories; look for and choose between alternative theories.

Justification: ability to
• provide evidence and/or arguments advanced in support of or against a conclusion; and participate in rational debates.

Critical thinking: ability to
• critically evaluate conclusions on the basis of relevant considerations above and beyond the evidence and/or arguments presented in support of or against the conclusions.