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Three Strategies for Interdisciplinary Math and Science Teaching:

A Case of the Illinois Mathematics and Science Academy

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Abstract

In this paper we explore three strategies that can be used to overcome the relative disciplinary isolation of science and mathematics in the traditional high school curriculum. The strategies are: *essentializing*, *contextualizing*, and *problem-centering*. The differences among these integrative strategies are rooted in the goals of the interdisciplinary curriculum and the purposes of the discipline driving the integration. *Essentializing* raises the scientific and mathematical facts to a level of fundamental concepts and helps establish *internal* connections within science and mathematics. *Contextualizing* efforts create *external* ties between the scientific and mathematical theories and their historical and cultural roots. *Problem-centered* integration (another strategy for *external* integration) mobilizes different disciplinary tools toward the solution of a pressing problem. We discuss the particular merits and constraints of each strategy, substantiating our claims with examples from programs and courses at the Illinois Mathematics and Science Academy (IMSA). Understanding the strengths and weaknesses of each strategy can help educators choose the optimal way to present their interdisciplinary material or to design hybrid approaches that build upon the strengths of several strategies.

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Introduction

The integrative teaching of science and mathematics

Nothing is easy about integrating mathematics and science into the rest of the pre-collegiate curriculum. The challenge comes from the specialization of knowledge in these areas, the use of different sets of terminology, as well as a tradition of teaching these subjects in a way that emphasizes singular facts and precise tools over broad concepts and generalizable ideas. Even within the sciences and mathematics, the separation between the different sub-fields is so rigorously maintained and the boundaries so clearly drawn, that the *internal* integration within them is no small task. As Rob Kiely, a historian of science at the Illinois Mathematics and Science Academy (IMSA), points out:

The nature of scientific and mathematical discourse is no longer intelligible to the average person. We are talking about a world where a chemist and physicist no longer speak the same language! What is happening to the scientific community? How is it separating itself from the social discourse? Is that unavoidable as a function of special expertise?

This is not just a philosophical or a sociological question, but also a pedagogical one. The divide between even closely related mathematical disciplines appears to be no smaller today than the divide between “the two cultures” of the sciences and the humanities that exercised C.P. Snow in 1959. But is it really unavoidable? What tools does a teacher in the high school classroom have to counteract this separation among the areas of knowledge? Can the teaching of mathematics and science be made more integrative with other areas of knowledge? If so, how?

In this study, we look closely at two kinds of integration. The first is *internal* integration *within* science and *within* mathematics, where different branches of the same tree are brought together through their common conceptual roots. The second kind of integration is *external* integration, where science and mathematics exchange ideas and tools with other fields outside of the paradigm of the scientific or logical-analytical method. The *external* kind of integration may appear to be a more definitive case of integration, as cross-paradigmatic bridges are established. However, the integration of sub-fields of science and mathematics may be a necessary first step to connect more distant epistemologies. Before scientific facts can be connected to historical events or turned into tools for tackling urgent social and technological problems, they need to be organized into the general concepts that underlie the discipline and unify it as one domain of knowledge. Without this initial conceptualization and unification of the separate sub-fields of science and math, further steps to connect science and mathematics to the outlying fields of knowledge are more difficult to take. Also, *internal* integration is not something to be taken for granted when it comes to establishing ties between scientific and mathematical sub-fields. The specialization of knowledge is *de rigueur* in those fields, and bringing the sub-fields together in the school curriculum represents a feat of

coordination, collaboration, and letting go of many ingrained assumptions. Therefore, both *internal* and *external* connections to science and mathematics are explored here.

Attempts to foster both the *internal* coherence among discrete mathematical and scientific sub-fields, as well as the *external* dialogue between the hard sciences and the humanities, have a long history in education. In the 1970's, the humanistic trend in psychology stimulated educators to center their curricula on core issues of the human condition. Protest against valueless science led to efforts "to align the teaching of science with social realities" or to use scientific concepts "to attack persistent problems of human experience" (Hurd, 1975). The spirit of connecting the natural sciences to social and human values produced a number of "unifying approaches" to the teaching of science in the secondary school curriculum (Lindsay, 1970). "A path to the greatest fulfillment and self-actualization" was envisioned in science (Maslow, 1971). Educators at the time, however, tended to downplay the fundamental distinction in the epistemological agendas of the natural sciences and the humanities, citing "differences in detail" and not of substance (Lindsay, 1970). Some educators proposed integrative strategies such as organizing the curriculum around urgent problems of humanity and showing science "as a product of culture and cultural evolution" (Ost, 1973). Most of these attempts, however, remained marginal to science education itself, possibly because they did not engage the scientific content in a deep and constructive way.

In recent years, the push to overcome the chasm between science and art, as well as the separation between biology and physics has reemerged. Today, the scientific community is achieving progress through breaking disciplinary seams and bursting into new domains that seemed hermetically sealed before. An enhanced rate of informational exchange in the last two decades has provided fertile conditions connecting disparate bodies of knowledge. Some scientific advances such as xenotransplantation or cloning technology make withdrawal of the sciences from broader social considerations lamentable.

Yet, despite this urgency for fluid interaction among sub-fields in the hard sciences and with the humanities, much of science and mathematics teaching at the pre-collegiate level continues to observe the bounds of narrow sub-fields. Furthermore, all too often such sub-fields are represented as (indeed reduced to) collections of facts and formulas to be utilized to address decontextualized problems. Higher levels of disciplinary thinking (e.g., developing mathematical proofs or constructing original testable hypotheses) are noticeably absent from many mathematics and science classrooms. Equally absent are attempts to open science to the humanistic concerns from which it has sprung.

Proposed here are three core approaches to the teaching of science and mathematics in integrative ways that differ from one another in form and purpose. These three strategies, which we call *essentializing*, *contextualizing*, and *problem-centering*, ask different questions of mathematics and science and serve different learning goals. They are a result of an analysis of exemplary teaching designs at the Illinois Mathematics and Science Academy. Our data were collected through semi-structured interviews with thirteen teachers, five administrators, and five students, as well as nine classroom observations.

We also compiled and reviewed a series of curriculum materials and publications by IMSA faculty¹.

The three integration strategies portrayed here represent distinct ways in which knowledge in different fields can come together in a classroom. The first strategy, *essentializing*, involves identifying core concepts that are central to two or more disciplines (e.g., change, linearity) providing a substantive bridge among them. We define the second strategy, *contextualizing*, as the connecting of a particular discovery or theory (e.g. theory of relativity) to the history of ideas of that time. The third strategy, *problem-centering*, involves enlisting the knowledge and modes of thinking in two or more disciplines (e.g., biology, mathematics) to address particular problems, develop specific products, or propose a course of action (e.g., develop a conservation policy).

A hypothetical example of an integrative unit on evolution can help clarify the differences among the strategies. Evolution could be discussed from multiple scientific and mathematical perspectives as representing the concept of *change over time*, for example. Biology, physics, and mathematics teachers can represent the concept of *change* in their respective disciplines. This type of disciplinary bridging illustrates the *essentializing* strategy. Alternatively, the material on evolution could be presented in class through a discussion of the historical and philosophical precursors of Darwin's discovery, his voyage on the Beagle, and the implication of evolutionary theory for what it means to be human. A teacher who takes this approach will be applying a *contextualizing* strategy. Yet another way to teach evolution in an integrative way is to present students with a tangible problem that could be solved with the help of some aspects of evolutionary theory. This would constitute a *problem-centered* approach to integrating material on evolution.

While the specific application of a strategy is, to a large extent, shaped by the disciplines involved (e.g., mathematics, science, history), analysis of teaching practices at other exemplary inter-disciplinary pre-collegiate programs has generally corroborated the validity of these strategies beyond the particular disciplines addressed in this paper. Our focus is on examining each strategy in depth—grounding our analysis in IMSA's classroom examples and highlighting the strengths and weaknesses of each strategy. The concluding section provides an overview of the inter-relationship among strategies and suggests constructive ways to combine them.

¹ Interview participants were selected based upon the recommendation of IMSA's Vice President for Educational Programs and Services, Connie Hatcher, and IMSA's President, Stephanie Marshall. Criteria for selection included participants' commitment to interdisciplinary learning and teaching as well as their thoughtful consideration of interdisciplinary pedagogy and assessment strategies. IMSA is uniquely suited to inform this inquiry for the following reasons: 1) it is institutionally mandated to promote excellence in mathematics and science education, 2) its faculty and administration are committed to integrative learning, 3) it upholds a rigorous disciplinary standard in its interdisciplinary work, and 4) it has produced a representative sample of these strategies over the course of a long history of experimenting with a variety of integrative pedagogies.

I. Integrative Strategy #1: Essentializing

Fostering conceptual thinking in mathematics and science

Essentializing is an integrative strategy designed to take students' thinking beyond the facts and tools of science and mathematics to the level of the underlying ideas that expose their relatedness. Algebra and geometry, physics and biology, history and geology can be brought together around core concepts such as *linearity*, *change*, and *scale*. Thinking conceptually about science and mathematics means thinking in terms of unifying scientific ideas or mathematical constructs that have the potential to produce sharable tools and understandings. Leonardo Frid (1995) summarizes the essence of this strategy:

Science, like other mythologies, attempts to retell this story in its own vocabularies: in numbers and formulas, in the documentation of pattern and repetition in Mathematics, Physics, Chemistry, and Biology; these are the dialects with which we retell our own existence; these are the links with which we write our scripts. But each discipline alone tells only one fraction of the story; harnessed together they give rise to depth, and tone, and color.

Essentializing the content of the different disciplinary vocabularies or “dialects” to core concepts or patterns that “tell a story” is at the heart of all integrative efforts at IMSA. The courses designed to teach students how to reason in mathematics and science are offered as part of the programs called Mathematical Investigations (MI) and Scientific Inquiries (SI). These are the main vehicles for the delivery of the science and mathematics curricula. The official brochure, describing IMSA’s MI Program, explains:

The main building blocks of the MI curriculum is the content/concept unit. Each unit addresses different content ideas centered around a single mathematical concept. This gives students insight into how different areas of mathematics fit together. For example, the Linear Thinking unit explores equations and inequalities, graphs, geometry, data analysis, and modeling into which the concept of linearity gives insight. The Function unit tackles functions and more general relationships from graphical, tabular, and algebraic viewpoints.

Integration in programs such as MI and SI happens within the larger fields of science and mathematics, rather than beyond them. MI, for example, is designed to present concepts from “pre-calculus mathematics, including algebra, geometry, trigonometry, data analysis, and discrete mathematics” in a unified and connected way (Marshall 2001). SI is similar to MI in that it is “the concepts, the principles, the deep constructs of a discipline” (Marshall 2000) that guide students through the curriculum, which weaves together earth sciences, life sciences, and natural sciences. An inquiry into the concept of “scale,” for example, spans the study of the diameter of an atom in contrast to the distance to the nearest star (physics and astronomy), the comparison of the speed of light

to that of a speeding bullet (physics), the investigation of an organism at a cellular level (biology and molecular biology), the investigation of the weather versus climate (earth science), and the study of geologic time in relation to the human lifespan (geology and human biology).

Students in the SI program are asked to uncover or build connections that are quantifiable, mathematically solid, and generalizable. For example, to answer the question of how the atmosphere acts as a radiation filter, students bring together chemistry (how bonds between the oxygen molecules in the ozone can be broken), physics (to describe how ray energy makes molecules vibrate similar to string action), and math (to calculate the frequency of these vibrations or oscillations per second) in order, as one student explains, “to find the wavelength necessary to break the bond between two atoms.” The student then translates this figure back into chemical or environmental terms to conclude that the “free oxygen atom (the result of an ozone split)” could potentially bind with an oxygen molecule in ClO and release into the atmosphere an unstable and polluting gas Cl_2 . “What is the implication of this chemical reaction for the environment?” the student asks. She goes on to answer, “Since the chlorine ends up unbonded at the end, it continues to destroy ozone.” It is not just a collection of chemical, physical and biological ideas that the student brings together, but a mathematical matrix of relationships that she constructs using the tools of different disciplines. The end product of this effort is a “strong correlation” between atmospheric pressure and atmospheric temperature, between the chemical reactions in the atmosphere and the probability of the preservation or destruction of ozone, given the physical and chemical constraints.

A combined MI/SI course, offered by teachers Susan Yates and John Eggebrecht, goes a bit further to connect concepts in math to those in science. Teachers in this team-taught course help students link a mathematical algorithm to a physical phenomenon. For example, the same concept of linearity, when examined through the lenses of both math and science, produces a joint understanding of a “linear relationship of energy and frequency” (MI/SI Materials). The goal of the curriculum, Susan Yates explains, is to have mathematics live “in the world beyond the x-y plane.” Yates and Eggebrecht have math and physics “speak in one tongue” — the tongue of fundamental scientific concepts. They explain that “establishing a common language, which bridges the discipline boundary,” means identifying core foundational principles that transcend both domains.

The SI and MI programs are good examples of *internal* integration of different sub-fields. Such integration results in unifying and preparing the whole field for further *external* connection to other disciplines. *Internal* integration efforts may not have the appearance of the integrative daring of the other interdisciplinary strategies, which break out of the boundaries of the scientific method. In fact, using unifying concepts to teach science and math curriculum is not the monopoly of integrative programs. The ability to build “coherent and rich conceptual webs” and flexibility to “relate the criteria by which knowledge is built and validated” (Boix Mansilla & Gardner in: Wiske, 1998) is described as one of the salient features of *disciplinary* learning at its best. Emphasis on conceptual thinking at IMSA indeed has been very successful in fostering solid and

purely *disciplinary* skills in science and mathematics. But the point where the disciplinary learning culminates and reaches full fruition is the point at which the interdisciplinary understanding begins to gain speed.

Essentializing, when applied to math and science, is not just the training ground for wider and bolder *external* connections. It is a rigorous, integrative activity in and of itself. In fields such as the arts and the humanities, conceptual linking occurs naturally and fluidly. History and literature constantly talk to each other to find answers to common questions of human existence. In science and mathematics, however, *internal* connections are more elusive, because of a tradition of separate terminologies, different methods of proof and verification, and distinct epistemologies.

Therefore, conceptual links even *within* the scientific and mathematical disciplines demand an effort on the part of the teacher and the student. Because the connections in this model occur at the level of discipline-grounded concepts and practices rather than general philosophical ideas, they involve a deliberate and often non-intuitive effort of coordination. They are produced “by design” (Marshall 2001), and not by happenstance. The role of the teacher as a translator across different systems of disciplinary representation is absolutely crucial and needs to be emphasized even at IMSA. According to Yates, who teaches mathematics, “Students on their own often don’t see the connection between using different variables to describe the same underlying pattern. They don’t see the pattern. They don’t see the transfer.” To them, the same notations have very different meanings in mathematics and in the natural sciences. “The subscripts in chemistry,” Yates points out, “mean something entirely different than subscripts in mathematics. Exponents in chemistry or the positives and negatives for the molecules, we use them differently in mathematics.” Teachers in both disciplines often fail to stop and think through the connections with students. “On the mathematics side,” Yates adds, “I don’t think we go around looking for those things necessarily. And, if mathematics teachers don’t talk about the nature of connection and disconnection between mathematical and chemistry concepts, the chemistry and physics teachers who use mathematics as a tool “don’t pick it up on the other end either.” Their thinking is, Yates describes, “I should not have to stop to talk about how I have to connect statistics to be able to come up with a regression equation to explain what I’ve done in the lab. It should be automatic transfer.”

But this kind of transfer is far from automatic for most students. The transfer of knowledge to new disciplinary material or “subscripts” is “hard” (Yates), because symbols and methods in different disciplines look and act differently. Yates suggests that “stopping to talk” about the underlying unity among concepts may be imperative in this case because otherwise “[the students] don’t see that they can change ideas, and teachers haven’t done a lot of integrating across disciplines.”

On the other hand, when teachers do take the time and effort to guide students through multiple representations of the same concept, students report “aha” moments. They discover the underlying coherence among facts and theories they had earlier regarded as unrelated. For example, student Danny Yagan describes how, with the help of his

calculus teacher, he began to see that “when you are talking about magnetic waves, you are talking about flux in the mathematics class, which is exactly the same thing — exactly the same mathematical representations.” It struck him that “these two systems do not only complement each other” but are “the same understanding but at different angles.” He continues:

My calculus teacher would always refer to calculus problems in physics as well as give us real-world examples of this abstract [notion]. He would put up on the board two ways of arriving at the same fundamental equations for projectile motion: ‘This is the calculus way, and this is non-calculus way. And, this is how it makes sense.’ Both ways. Literally, step by step on each way. He was a really good teacher in that respect. Even in physics course, algebraic equations were introduced. And it made sense to me. Later on in calculus, my teacher applied what we learned in calculus to those motion equations.

Once the student has been guided to discover the essential unity between the physical and logical worlds, he or she may be able to go further and seek more challenging connections to the humanities and social sciences. What helps to close the gap in the SI program is the inclusion of epistemological discussions about the nature of science and the scientific method. Sensitizing students to what it means, in the words of IMSA’s humanities and history of science teacher Rob Kiely, “to think scientifically, to frame a question, the basics of good lab work, the relationship between data analysis, data collection, conclusion, what a scientific theory is and how theories change, the revisionist character of scientific thinking,” makes them ripe for seeking and finding connections within and beyond the scientific and mathematical disciplines.

Thus, *essentializing* is a strong model for integrative work. It raises factual information to the level of conceptual abstraction from which transfer becomes possible. Still, in the case of math and science, which are characterized by high specificity of terminology and methodology and the cumulative nature of knowledge, *essentializing* represents a substantial pedagogical and curricular effort. It requires massive coordination, re-sequencing, and restructuring of the material around unifying concepts rather than disciplinary lines. Links are built one plank of solid proof at a time, and therefore the process is more laborious and time-consuming. It cannot be accomplished in any comprehensive manner without a firm institutional commitment and the willingness of the teachers to work together in a new way. Teachers need to be deliberate and consistent translators of disciplinary languages so that the students can see symmetries and piece together a coherent story told, as Frid put it, in different disciplinary “dialects.”

II. Integrative Strategy #2: Contextualizing

Weaving mathematics and science into the history of ideas

Contextualizing is an *external* integrative strategy that places scientific and mathematical knowledge in the context of cultural history and the history of ideas. Science and

mathematics are represented not so much by their separate theories and practices but by their common philosophical foundations and historical roots. Historical, philosophical, or epistemological foundations of a particular scientific theory can all serve as *contexts*, or as the “organizing centers of the integrative curriculum,” as one of IMSA’s top administrators, Michael Palmisano, describes.

Formalized in the Perspectives Program, which represents a history of ideas curriculum, and in their humanities courses, *contextualization* is an important integrative strategy at IMSA. Rob Kiely, a faculty member who is actively involved in revising the Perspectives Program, explains that the goal of the program is to understand “the development of scientific thinking chronologically in the context of the history of ideas.” Questions that are part of this integrative inquiry might include, “Why did scientific thinking develop in Western Europe, and how was that related to Greek philosophy, revealed religion, political circumstances up until the 17-18th century? Why is it necessary to understand St. Augustus to understand Isaac Newton?” Kiely goes on to say that, for this kind of a curriculum “definitions of truth, ways of knowing — that’s what’s really central.” The “connecting tissue” between the natural sciences and the humanities are not the core concepts of those disciplines, but rather the philosophical, historical, and cultural roots of those concepts. “Roots, not the branches,” Kiely emphasizes.

A good example of the application of this strategy occurs in a Perspectives Program seminar on the development of navigation in the 16th century. Astronomy, astrology, geometry, metallurgy, painting, geography, shipbuilding and sailing came together seamlessly in this seminar to illuminate the emergence of abstract thinking about space. A history teacher talked about the navigational techniques, instruments, and voyages of exploration of the time; a math teacher explained analytical geometry and the development of graphing techniques that lead to two-dimensional representations in terms of latitude and longitude; a physics teacher briefed the students on “modern global positioning satellites — how we now use abstract notions of space, rather than orient by stars;” and an art teacher brought in the notion of three-dimensional space in Renaissance painting. As a result, mathematics, physics, and art were brought together as reflections of a particular moment in history and as products of a certain culture.

Unlike *essentializing*, which focuses on building *internal coherence within* the fields of science and mathematics, *contextualizing* achieves broad *external* connections between distant disciplinary shores. While making mathematical concepts connect to humanist or artistic concerns seems almost an impossibility in *essentializing*, it is not a problem in *contextualizing* because math is reinterpreted as a carrier of a particular philosophy or a reflection of a particular historical moment.

The strength of this model is its broad reach of disciplines, its ability to move easily and seamlessly across distant epistemologies, and its support in making abstract knowledge personally meaningful. Students in these classrooms reported profound experiences of suddenly seeing how once disconnected ideas reverberate in culture and time and become relevant to themselves. Doug Robinson, a Perspectives student, reported that the world of mathematical abstraction suddenly came alive in his mind through this cultural and

historical reference. To Kiely, integrating the teaching of science with intellectual history is the optimal form of integration:

The only way to really integrate science and the humanities in a fundamental way is around the definition of truth. The idea is to demonstrate how scientific thinking proceeds from the epistemological efforts of humanity and show it against the broad context of human ways of knowing — mythological, religious, and philosophical — how it proceeds from a very complex dialogue on what is truth.

While the *contextualizing* strategy taps some important aspects of the discipline, such as its methodological and philosophical foundations, it leaves out other crucial elements such as scientific and mathematical practices, facts, and proofs. Kiely admits that perfecting particular techniques and methods of math is not the objective of the *contextualizing* approach. The most significant impact of this kind of integration is not the advancement of lab techniques and experimental procedures. The purpose of *contextualizing* efforts, according to Kiely, is to consider how science is relevant to the rest of the world:

[Scientists in the 21st century] do not lack technical expertise; they lack wisdom. We live in a world where biology enables our ability to manipulate the human genome ... [which] is far ahead of our legal or philosophical ability to regulate how to use this knowledge in fruitful ways. How do we help scientists express the nature of scientific thinking to the general public? How do we help scientists think in an ethical context? How do we help scientists decide whether or not certain questions should be pursued?

These are the questions that the *contextualizing* of science, math, and technology can effectively address. Students typically come out of these classes transformed and inspired to go further in science and mathematics because their fields have been made relevant to their lives.

This model of integration does no less important work for science and math than the conceptual deepening of scientific facts and theories. While it does not directly teach advanced techniques, it puts the disciplines in a broader context and thus can teach students about the social responsibility of science and technology. Social, historical, or epistemological *contextualization* of science and math is in no way a replacement for *essentializing* scientific or mathematical concepts. The history or philosophy of science is not a substitute for science, nor is it desirable to turn a lab into a venue for a philosophical debate. These two models serve different purposes and do different kinds of work in the classrooms. Their coexistence in the school curriculum, perhaps even in the same classroom, could potentially maximize the strength of each model while compensating for some of their limitations.

III. Integrative Strategy #3: Problem-centering

Applying math and science to solving real-world problems

Focus on a tangible problem rather than on enhancing disciplinary or metadisciplinary understanding defines the third integrative strategy and determines a special kind of relationship among the disciplines.

IMSA is well positioned to represent a *problem-centered* curriculum at a pre-collegiate level. Problem-Based Learning (PBL) is the pedagogy that IMSA developed and exported to other schools. Although authentic PBL classrooms that follow the precise protocol that IMSA devised are rare even at IMSA, *problem-centering* of the curriculum is common in all of its classrooms.

What does *problem-centering* look like in practice? According to IMSA's Stepien and Gallagher (1993), a problem-based unit may present students with "an ill-structured problem" from the real world, one with multiple points of entry. For instance, students may be asked to advise a couple whose fetus has been diagnosed with anencephaly on whether they should terminate the pregnancy. Decision-making and action is an important charge of *problem-centered* learning. Learning is transformed from a contemplative process that generates deeper self-understanding and disciplinary knowledge to an action-driven series of steps. These steps typically include answering three main questions: "What do we know? What do we need to know? What should we do?" (Stepien, Gallagher, & Workman, 1993).

The way mathematics and science participate in *problem or context-centered* integration differs from the way they participate in the *essentializing* effort. To answer the question "how would you build a colony on Mars?", for example, students bring in sociology, biology, physics, chemistry, technology, and psychology and put them through the convergent lens of a problem. This lens reveals the parts of the disciplinary content that need to be borrowed on a short-term and single-problem basis. Similar to *contextualizing*, *problem-centering* can bring different fields in close interaction with one another and thus foster broad *external* connections between the sciences and other fields.

Although *problem-centered* learning could be part of any classroom, some disciplines seem to be more regular and consistent users of this strategy. These tend to be social science disciplines, such as ecology or economics, that target socially relevant problems as the subject of their analysis. An ecology teacher at IMSA, John Thompson, routinely uses biology, chemistry, earth science, literature, foreign languages, visual arts, and computer technology to address environmental issues. Thompson's classes involve *doing* ecology rather than learning *about* it. The classes feature field activities, digital imaging analysis, prairie populations studies, computer labs, orienteering, soil community analysis, among others. An *Energetics* unit, for example, is explored through statistical analysis (mathematics), biochemistry and thermodynamics, discussion of the value of the fur trade in the colonization of North America (history), writing a research paper (English), and using personal digital assistants (PDAs) for data collection (technology). Students typically come out of these experiences with enhanced knowledge of particular

aspects of particular theories, but more important, they produce a plan to resolve a complicated environmental issue.

Michael DeHaven's economics class, likewise, depends on borrowing languages and tools of other domains to address financial issues. To advise Goldman Sachs on whether a privately held partnership should become a publicly traded corporation, for example, students have to apply microeconomic theory (economics), "interpret the significance of game theory on market structures" (mathematics), and "assess government roles in regulating market structures" (political science). These are just a few disciplines whose tools are put to the service of an "ill-structured problem" regarding the public offering. Addressing such problems involves mapping the problem territory, bringing together all of the relevant disciplinary tools in order to provide a rich description of the problem, isolate its "primary issue," and define what the solution might be. In the process of generating an answer from these various sources, students confront differences in perspective and have to reconcile them. Thus, the final report is a synthesis of mathematics, science, sociology, and other disciplines.

The advantage of this pragmatic orientation toward interdisciplinary interaction is that it brings together a wide range of disciplines. Also, the disciplinary content and tools of these disciplines are used with precision and rigor rather than in a generalized and abstract way. Unlike *contextualizing* science and math, in which the conversation among disciplines happens at a broad level of metadisciplinary reflection (e.g., how the theory of relativity relates to the philosophical questioning of certainty under way in late 19th century), the scientific/mathematical tools and procedures are engaged in the *problem-centering* approach thoroughly, if not extensively. As a result, the student might actually perfect his/her skill of statistical analysis or learn more about molecular weights as he/she assesses the contamination of groundwater. When mastery of disciplinary tools serves a compelling problem, significant and highly motivated learning of mathematical and scientific theories can occur.

The constraint of this model is its potential decontextualization and narrowing of the discipline. *Problem-centered* models often tap selective disciplinary procedures (e.g., Fibonacci numbers from mathematics, the concept of land ownership in the Middle Ages from history) without a thorough exploration of their wider philosophical or methodological underpinnings. According to one student at IMSA, Doug Robinson, "You may understand one problem, but you may not see the underlying principles." Also, he continues, "You may get at certain fundamentals more than others." Both the ecology teacher John Thompson and the economics teacher Michael DeHaven are aware of these pitfalls and go the extra mile to have students build up a broader context for the problem. For example, they guide students to see the data (e.g., monetary crisis or pollution) as results of human action that are culturally shaped and politically changeable. In doing so, they complement the *problem-centered* model with a *contextualizing* approach that allows students to gain a broader perspective. *Problem-centering* tends to be a highly transferable strategy. It offers the point of connection that provides motivation for negotiating and reconciling disciplinary differences. Science and math often find

themselves as valuable partners in this conversation as they lend tools and practices for collective inquiry into a complex issue.

Summary

Strategies and their inter-relationship

The three vehicles of integrating science and mathematics into the pre-collegiate curriculum reveal different symmetries and relationships among areas of knowledge. They serve different purposes and engage different parts of the discipline. The table below provides a summary description of the strengths and weaknesses of each of the described strategies and proposes ways to address potential blindspots of different strategies in classroom practice.

Strategies	Strengths	Weaknesses	Ways to compensate for weaknesses
<i>Essentializing</i>	<ul style="list-style-type: none"> • Rigorous correlation of related knowledge areas • Fosters inner coherence in the broader field of science and mathematics • Exchange is rich in discipline-specific content (e.g. theories, concepts) 	<p>IV. Limited breadth of connection, constrained to sub-fields of science and mathematics only</p> <p>V. Does not provide a personal reference point for the learner</p>	<ul style="list-style-type: none"> • Discussions of scientific methodology and historical circumstances of discoveries • Presents some of the content through real-life problems
<i>Contextualizing</i>	<ul style="list-style-type: none"> • Ease of making external connections between unrelated areas of knowledge • Scientific knowledge is made personally relevant • Philosophical roots of science and mathematics are explored • Students' awareness of the implications of science and mathematics for society at large is heightened 	<ul style="list-style-type: none"> • No intensive exploration of the disciplinary facts and practices is undertaken • Disciplinary dialogue happens at a metadisciplinary level — level of social meaning of mathematics and science 	<ul style="list-style-type: none"> • Methodological discussions might help introduce more of the disciplinary content of science and mathematics • Examples of how a certain problem was addressed differently in a different time period might help illuminate both the content of the problem and the changing times
<i>Problem-centering</i>	<ul style="list-style-type: none"> • Students' attention and creativity are fully mobilized by the urgency of the problem • Inspires activist approach to learning and knowledge in students • Motivated and thorough mastery of the disciplinary content (e.g. facts, practices, theories) occurs as a result • Unrelated disciplines come together easily in this model, as differences between them are addressed decisively and pragmatically 	<ul style="list-style-type: none"> • Learning is highly targeted to the problem and therefore coverage of the field is limited to relevant tools and theories only • Reflection and deliberation on the discrepancies in the disciplinary approaches is minimal 	<ul style="list-style-type: none"> • Historical and cultural survey of the problem can help find additional solutions or understand the complexity of the problem more fully • Broader view of the whole field of mathematics or science can also generate new solutions and perspectives on the problem

Thus, *essentializing* is designed to deepen disciplinary understanding and build coherence between disciplines at the level of core concepts. Stringent disciplinary standards govern the connections that are generated; tight correlations between concepts in different disciplines are sought. This tends to put a limit on the length of the bridge that is constructed. The strength of this model is in the richness of disciplinary content that is being represented and the tightness of correlations that are being established across different disciplinary representations of core concepts.

By contrast, *contextualizing* helps science and mathematics reach out beyond themselves by placing them within the contexts of cultural evolution and the history of ideas. Woven into the fabric of the history of civilization and addressing fundamental questions of human existence, scientific and mathematical discoveries become a strong and inseparable thread. Not only are the neighboring disciplines of trigonometry and algebraic functions brought together, but one can also imagine a classroom where they enter into a conversation with history or poetry. Disciplines here act as worldviews, products of a certain civilization at a certain moment in time, or threads in the fabric of history.

Problem-centering uses an ill-structured problem, rather than history or culture, as a point of connection between science or mathematics and any other discipline. It makes connections between ideas precise and pragmatically relevant. No investigation of broader disciplinary context of the issue or different tools is typically undertaken, nor does one typically spend much time on concept-building or deriving historical meaning from mathematical or scientific data in this model. *Problem-centering* as a strategy pursues a clearly defined goal: to resolve an urgent, tangible, and complex problem that invites or demands input from several fields. Unlike the *essentializing* or *contextualizing* models, which are guided by a more contemplative task of building coherence among areas of knowledge or promoting self-understanding, the *problem-centering* model is aimed at generating critical action. The integrative strength of this model lies in its flexibility to reach out and include a wide spectrum of disciplines as well as to encourage the mastery of disciplinary content. The blind spot of this strategy could be the pragmatic narrowness of the disciplinary exploration. Nevertheless, the motivational and integrative power of this strategy is notable.

Going back to our opening example of a unit on evolution, it is easy to show that the three strategies of integrated teaching are not mutually exclusive. In many classes and in the hands of many good teachers, several strategies can work together. Very often, a historical reference to Darwin's voyage and the discussion of the significance of his ideas for contemporary scientific thinking accompany a biological survey of the theory of evolution. Instructors may also touch upon the practical implications of the theory of evolution for agriculture or genetic counseling. Understanding how each strategy works can help teachers achieve the most productive synthesis in the classroom.

So, mathematics and science teachers can learn from the humanities faculty about the history of ideas in their fields, and center their curricula on problems from the real world. Conversely, a *problem-centered* pedagogy would profit from a richer historical *context*

(e.g., discussion of the culture of Wall Street and how it evolved in the context of a capitalist economy) and *essentializing* (e.g. exploration of the mathematical concepts and axioms behind the statistical methods). *Contextualizing* efforts, in turn, may benefit from a reminder of the rigor of correlations that exist when such connections are made between scientific or mathematical concepts.

While the above analysis is based on classroom practices at IMSA, teachers in any school setting and in any subject area can benefit from keener awareness of the different frameworks that they have available to them as they design their own interdisciplinary curricula. By inviting humanities and social science teachers to provide an historic context for scientific discoveries, for example, or by *problem-centering* of the inquiry in any subject area, they will tap certain kinds of learning opportunities and limitations associated with the application of that strategy. They will have to search for hybrid ways to build a particularly effective interdisciplinary exchange that reflects their teaching goals.

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