GAEDE INSTITUTE
for the Liberal Arts

Reinforcing the Triviuum, Reimagining the Quadrivium, and Promoting the Good Life for All: Why the Sciences and Humanities Need Each Other in the Liberal Arts

by Stephen M. Contakes

Delivered February 27, 2015
at the Fourteenth Annual Conversation on the Liberal Arts
Westmont College, Santa Barbara, CA

Reinforcing the Triviuum, Reimagining the Quadrivium, and Promoting the Good Life for All: Why the Sciences and Humanities Need Each Other in the Liberal Arts

Stephen M. Contakes
Assistant Professor
Department of Chemistry
Westmont College

Abstract: Medieval and Renaissance visions for the liberal arts might serve as a useful starting point for considering whether and to what extent STEM disciplines may function as liberal arts. This is particularly so since the medieval liberal arts functioned as a program of instruction in sound thinking and represented what educated persons needed to know while the renaissance liberal arts explicitly recognized that educated persons influence the cultures of which they form a part. In this respect STEM education programs can function as liberal arts, provided they retain the medieval and renaissance emphases on sound thinking and social responsibility, respectively. In fact, the STEM fields share many similarities with the themes of the medieval trivium in that they

- Apply reason (logic) and experience to make sense of the physical and material reality.
- Employ symbols and mathematical models (grammar) to describe, manipulate, and draw out the implications of scientific ideas and findings.
- Purposefully use employ structured discourses (rhetoric) in the form of scientific papers, talks, posters, proposals, *etc*… to inform (teach), argue for (persuade), and memorably impart insight (delight) when communicating about their work.

Science is also like the four mathematical sciences of the quadrivium in that its mathematized picture of the world imparts significant understanding of the nature of physical reality while also raising and constraining questions for philosophy, theology, and other humanities. Indeed, STEM disciplines are can function as the heirs of "natural philosophy" in their efforts to develop a coherent account of the working of the physical and material cosmos, sometimes even using approaches, ideas, and concepts that are extensions or corrections of classical ones (*e.g.* reasoning from experience, atomism, geometry, *etc*…). Science's influence on culture through its picture of reality and influence on technology also provide opportunities for STEM disciplines to participate in conversations with the contemporary humanities. Indeed, by taking humanities disciplines seriously and treating them as partners in conversations about the STEM's impact, the STEM fields can encourage the humanities to avoid unhealthy forms of disciplinary isolationism and properly recover the original renaissance ideal of the humanities as culture-makers through education. In turn, STEM practitioners can employ resources from the humanities to better live out "the good life" in the context of a scientific vocation.

Introduction

The last 25 years have seen a sharp decline in the number of traditional liberal arts colleges; some have closed their doors while a much larger number have subtly shifted their focus away from traditional liberal arts programs towards more professional ones, essentially becoming "lite" versions of research universities.[1] Meanwhile traditional liberal arts disciplines have fared little better within the research universities themselves as students increasingly choose more vocationally-promising STEM[1] majors over those in the humanities.[2] This grassroots rejection of the humanities and movement towards viewing higher education as a form of job training is mirrored in the political realm where the liberal arts have come under attack by politicians who question the wisdom of public funding for disciplines they feel do little to prepare graduates for future success in the workforce.[3] Although such feelings are at best questionable,[4] they resonate with popular perceptions that the liberal arts contribute little to the social good.

At first glance it seems odd that the liberal arts would be perceived of as irrelevant, seeing that one aim of the liberal arts is to prepare students to function responsibly as free citizens in society. It may be that an overly restrictive definition of social utility underlies opposition to the liberal arts, namely one in which "useful" training is defined as that which provides immediate post-graduation economic benefits in the form of a high-paying job. Liberal arts educators nourish this mindset when they define the liberal arts in opposition to the specialized "practical" training of vocational or professional schools. In these schemes practically useful disciplines like medicine, business, the law, engineering, nursing, and, increasingly, natural sciences such as physics, biology, and chemistry are held to be outside the liberal arts while humanities disciplines like English, philosophy, and the arts are assumed to function as liberal arts in their own right.

Even when the liberal arts are held to be distinguished from the STEM disciplines by their emphasis on broadly integrated learning, ability to promote self-reflection, and the development of critical thinking, communication and interpersonal skills, students and their parents can find it difficult to believe that these skills are somehow uniquely the province of the liberal arts. Since STEM graduates are popularly regarded as sharp critical thinkers[5] it can be difficult for these prospective liberal arts constituents to imagine that the disciplinary training received by scientists, engineers, and other professionals merely prepares them to function as technicians operating within a tightly-defined paradigm to attain crudely utilitarian ends. Indeed, although some segments of science and technology (like the chemical industry) suffer

---

[1] STEM stands for Science, Technology, Engineering, and Mathematics.

from tarnished public images, there is a widespread feeling that the net effect of the STEM fields has been a massive increase in human knowledge accompanied by an equally dramatic increase in mankind's standard of living. In short, for many the STEM disciplines exemplify the ideals of human intellectual achievement and its social benefits - exactly the sort of thing the liberal arts should be careful to avoid defining itself against.

A better way forward, perhaps, might be to do some hard thinking about what exactly constitutes liberal education and the liberal arts, and whether and to what extent disciplinary training in STEM disciplines and vocations can or should function as a part of a good liberal arts education. Indeed, the medieval liberal arts included both a trivium of grammar, rhetoric, and logic and a mathematical quadrivium of music, arithmetic, geometry, and astronomy that were regarded as necessary preparation for (*i.e.* not an alternative to) vocational training in learned professions. Further, although there are striking differences between the role and practice of astronomy and mathematics in medieval Europe and the nature and function of their contemporary counterparts,[6] the quadrivium included much of what would today be regarded as STEM education. For instance, medieval "geometry" was essentially Euclidean, even though its connections to other fields, particularly philosophy and theology, were also explored.

Today it would be unwise for the sciences to expand their aims to encompass philosophy and theology; science's achievements have come in part because science limits itself to describing nature's behavior and explaining phenomena in terms of efficient causes and so it is ill-suited for answering questions about purpose and meaning in the universe. Nevertheless, science's insights often raise interesting philosophical and theological questions while (as this essay will illustrate) its approaches retain important features of the medieval and Renaissance liberal arts.[7] Indeed, my aim in the present paper is to suggest that STEM disciplines can function as liberal arts when taught as an opportunity to develop sound thinking and encourage right living as well as an opportunity to learn about the operations of the physical and material universe and the methods humankind has developed for studying and manipulating them.

I cannot claim that STEM education is always taught as a liberal art and so will focus on demonstrating instead that the ideals of professional STEM education and liberal arts education are mutually reinforcing. For example, good" chemical education envisions chemistry not primarily as a body of knowledge or means for solving technical problems but as a lens for encountering physical and material reality, a way of life in a community of scientific practice, and participation in a social enterprise that desires to achieve tangible and intangible social “goods.” Moreover, “good” chemical education functions as a handmaiden to other fields of intellectual inquiry in that chemistry presents a picture of physical reality worthy of being reflected upon using disciplinary approaches better suited to address issues of meaning and value. In short, other liberal arts disciplines can benefit from chemistry but also help chemists better interpret chemistry and situate it in the context of life’s “big questions.” However, in order for this to take place a liberal chemical education must not merely be chemical education plus courses in the humanities and arts. Instead a liberal arts chemical education must be able to reinforce the traditional liberal arts and embody liberal arts ideals in both the content and methods it employs to do chemical education itself.

Many chemists (and other STEM educators) might feel ill-equipped to teach chemistry in a way that reinforces the liberal arts, thus a secondary goal of this paper will be to suggest a few points of connection between chemistry and several elements of liberal arts education. Specifically, the highly-professionalized chemistry curricula promoted by the American Chemical Society provide opportunities to reinforce the Triviuum by helping budding chemists better think broadly, function well in community, and engage in appropriate self-reflection. Moreover, the disciplinary content of chemistry and nature of scientific practice provide opportunities for chemistry to serve as part of a reimagined Quadriviuum in which students are encouraged to explore questions of truth, value, “good” living, and responsibility with philosophers and theologians and evaluate the situatedness of scientific knowledge and the scientific enterprise by engaging in dialogue with humanities and social science scholars.

In order to see how this might take place, it may be helpful to first examine current and historical conceptions about the liberal arts.

Whose liberal arts? Whose science? Whose culture?

The notion that professional training and the liberal arts are incompatible is not without basis, although in some respects it depends on particular conceptions of the liberal arts and particular schemes of professional education. Both of these, in fact, have changed somewhat over time in response to the needs, prejudices, and interests of the societies in which they functioned. In the classical Greek society from which the contemporary liberal arts is derived, education was reserved for free citizens who possessed the necessary leisure to pursue them, in contrast to the more practical training acquired by those who needed to practice a trade in order to earn their bread.[8] There is some indication that these “liberal arts” were somewhat less than humanizing; the Stoic philosopher Seneca criticized them for providing an education that was narrowly focused on acquiring knowledge and contributed little to moral development. Nevertheless, the intellectual focus of Greco-Roman liberal studies continued in the seven medieval liberal arts which included both a preparatory *Trivium* of grammar, rhetoric, and logic followed by a subsequent "scientific" *Quadrivium* of arithmetic, geometry, music, and astronomy. Although the latter were not sciences in the contemporary sense, most medieval thinkers were expected to be conversant with the natural philosophy of their day. Thus it is not entirely surprising that Albertus Magnus was as conversant with both metallurgy and theology while Isaac Newton's writings on theology were more extensive than his scientific ones.

It was the Renaissance humanists who moved the liberal arts away from their original intellectual focus. In particular, the humanists re-envisioned the liberal arts as a means for civilizing, culturing, and "humanizing" students. They also hoped that their students would in turn humanize the communities of which they were a part. In short, these humanists specifically re-envisioned the liberal arts with the social good in mind. They even replaced the trivium with a much broader program of studies called the "humanities" which included disciplines like history, languages, and the arts which they envisioned as useful for understanding, engaging, and inspiring the wider culture.

It should also be noted that whereas the medieval liberal arts were regarded as a sort of preparatory general education that qualified one as educated and prepared students for further study in learned professions like theology and the law, these new humanities also served as respectable disciplines in their own right. Over time this would meant that they would begin to function less as a coherent body of preparatory material[9] and increasingly as a federation of disciplinary islands, albeit ones still grounded in classical languages, literature, and approaches to learning.

In addition to the humanities, contemporary American liberal arts colleges often regard the sciences as liberal arts. Nevertheless, both now and in medieval Europe their status could be somewhat ambiguous. Among the ancients and medievals, technology and the trades were regarded as "vulgar" and inferior to the liberal arts. Over against the seven liberal arts the medievals even recognized seven "mechanical arts" that included skills now associated with the trades such as cooking and weaving along with "STEM" fields like metallurgy, architecture, and medicine. In general, however, these tended to function more like craft traditions than the liberal arts fields. Nevertheless, some of these "craft traditions" employed definite physical theories to guide practitioners' work and thus could also be regarded as a sort of "applied geometry."[10] In fact, the sciences which eventually began to take their place alongside traditional liberal arts fields merged these craft traditions with natural *philosophies* rooted in Greek philosophical thought. The atoms of modern chemistry and physics, for instance, owe much to both the alchemical craft tradition (which applied Greek element theories to chemical problems) and the French humanist Pierre Gassendi's efforts to rehabilitate and Christianize Epicureanism (including ancient atomism) during the early modern period.[11]

Indeed, even though the study of nature was recognized as distinct field of inquiry since antiquity specialized programs of scientific education are products of the latter 19th century.[12] In some parts of America, at least, it appears that the trivium had degraded into a system of education that emphasized rote recitation and the mastery of classical languages; as a result many felt it was less relevant to the needs of the technology and progress-oriented society of the late 19th Century. Thus Universities sprung up or remodeled themselves along the lines of Germany's research Universities, which emphasized technical training, research, and laboratory work. Even at traditional liberal arts colleges traditional classical curricula were modified or replaced. Harvard, for instance, transitioned to an elective system specifically in order to carve out space for science and engineering students to undertake additional laboratory work.[13]

In adopting specialized programs of science education, educational reformers sought primarily to carve out space for appropriately rigorous programs of science education, not to disparage classical learning.[14] Nevertheless, as the world of the 19th and 20th Centuries came to be filled with the fruits of science and technology, scientific knowledge increasingly came to occupy a privileged place in western culture's plausibility structure. Over time some traditional humanities disciplines even became marginalized and abandoned the Renaissance humanist mission of salting society with cultured elites.[15] Some, appropriately recognizing the cultural-situatedness of meaning, shifted their interpretative focus away from the discovery of patterns for objective understanding towards an emphasis on discourse and interpretation as objectives in themselves, effectively abandoning the search for objective knowledge to the sciences.[16] Others adopted the language, methods, and approaches of "science" to reshape themselves into "social sciences." All disciplines, however, became more cloistered and self-referential. The sciences, for example, became increasingly mathematicised and more technical, necessitating even more specialized programs of study and rendering their content less subject to evaluation by educated non-specialists, even ones in other scientific fields.[17]

As both the sciences and humanities became more specialized and technical it became more difficult for educated persons to be highly-conversant in both. By the 1950s C.P. Snow was even able to speak of science and the humanities as two separate cultures. However, while Snow simply noted a trend and expressed hope that "third culture" intellectuals would arise to bridge the gap, by the 1980s and 90s the recognition of estrangement sometimes began to take on the character of blame with STEM professionals chiding scholars in the humanities for their lack of meaningful engagement with science and technology, or even culture as a whole. Sometimes these efforts took on a farcical character, as in the midst of the postmodernist science wars when the physicist Alan Sokal successfully submitted a nonsensical hoax article on the "hermeneutics of quantum gravity" to the journal *Social Text*, a move which he claimed might help expose the fallacies of extreme postmodernism.[18] Other scientists offered more helpful and sympathetic critiques, however. For instance in 2003 the engineer Louis Bugliarelo later complained that the humanities lost their way by turning away from a science and technology rich culture towards self-reflection and self-criticism. Specifically, he claimed that the humanist academic disciplines of the renaissance had degenerated into narrow-minded self-referential cliques and that, as a result, the liberal arts had lost their "ability to illuminate and guide society."[19] Bugliarelo traced this to a lack of meaningful engagement with science and technology, which forms such an important part of contemporary culture.

Not all humanities scholars would agree that the humanities should or can guide society, however. Stanley Fish, for instance, claims that the disciplinary structure and aims of the contemporary humanities ill-fits them for a culture-shaping role[20] and that, in any event, literary study itself does not serve a humanizing function.[21] If Fish is right about literary study (and I suspect he is),[22] a great books approach to culture-making is bound to be ineffective in the contemporary academic culture.[23] However, even so, it would not follow that the humanities have no role at all to play in the shaping of human culture. Not only are the humanities part of mankind's intellectual heritage and thus valuable in themselves, they can serve as an effective counterbalance to overzealous attempts to apply scientific methods outside their realm of applicability.

The Harvard psychologist Steven Pinker's recent complaint about his humanities colleagues' seeming unwillingness to bring scientific insights into their disciplines[24] illustrates the danger of ill-conceived applications of science. Pinker justifiably castigated humanities scholars for allowing liberal arts graduates to matriculate with little understanding of science and for adopting a caricature of science as an imperialist purveyor of unintended harms. However, Pinker had somewhat missed the point in complaining that humanities scholars were resistant to science's attempt to contribute to their fields. The issue was not so much that the humanities scholars were rejecting science as that they perceived particular scientific contributions to their fields to be at best unhelpful.[25] Indeed, the case which Pinker settles on – the "scientific" denial of religion in the form of the New Atheists– is a good example. It is not that the New Atheists have attempted to relate science and religion or even that they deny the validity of insights from religion *per se*; rather it is that the New Atheist writings have been marred by bad arguments and shoddy scholarship that ignores important insights from the humanities.[26] In fact, in failing to take important aspects of religion and religious texts seriously, the more scientifically-dazzled New Atheists were guilty of just the sort of oversimplifications and distortions that Pinker alleges of their humanities scholar detractors.

If the above analysis is correct, a central challenge for liberal-arts proponents is to restore the humanities to their rightful place alongside science as a culture-influencing and knowledge-generating enterprise. This will probably involve conversations within the humanities themselves, perhaps about the role and limits of scientific methods in humanities scholarship and how insights from the post-modern humanities should best be accommodated in humanities which see themselves as sources of genuine knowledge. However, as the work of a STEM scholar interested in advancing the liberal arts, this essay will not examine those internal conversations in any detail. Instead, it will focus on how the sciences generally, and science education in particular, can work together with the humanities in a re-envisioned liberal arts.

Can the liberal arts benefit from a return to earlier ideals?

One reason for the cultural estrangement between the STEM disciplines and humanities is their disciplinarily insular approaches to education, in which cross-talk occurs almost exclusively through a series of general education courses. Thus humanities majors, many of which enter college having been told they lack a "math and science brain," are held to be broadly educated with only a cursory knowledge of the sciences acquired through specialized "nonmajors" courses. Had they taken the regular STEM majors courses, however, the humanities majors would have fared little better since STEM major courses tend to focus almost exclusively on disciplinary content and discipline-associated skills. This is not entirely inappropriate but it means that humanities majors can get away with a cursory understanding of the sciences and their role in society while STEM majors can get away with encountering the liberal arts piecemeal in a scheme that allows them to treat the humanities as a sort of GE intellectual shopping mall – a trendy place they can wander through to encounter interesting curiosities and where they might even pick up a few useful items (like speaking and writing skills) but which, unlike the grocery store and medical clinic, has little to do with the serious business of life. To the extent that STEM graduates function as mere technicians, the humanities have let them get away with it. Little wonder, then, that the humanities have suffered of late. Remaining narrowly entrenched in disciplinary conversations and allowing oneself to be treated as a smorgasbord of hobbies with vocational benefits is hardly a pathway to cultural relevance, let alone an effective way to serve the social good.

One way forward might be to return to those earlier liberal arts ideals (and they were only ideals) which viewed the sciences and humanities as part of an interconnected and interdependent body of knowledge and in which the humanities and sciences worked together to shape human culture.[27] Before we can consider how to redress any deficiencies in this respect, however, it may be helpful to first consider how disciplinary boundaries in the contemporary academy might represent obstacles to broad integrated learning and appropriate cross-disciplinary influences. At most institutions academic departments tend to function as self-contained entities and cross-talk occurs through sporadic college wide events and at the individual faculty level. Here, however, there is a problem. Wielding the success of science as a warrant, scientists rarely appreciate the disciplinary content or respect the methods of inquiry in the humanities; a few have even offered scientific insights as an end-all arbiter for problems in the humanities. In contrast, scholars in the humanities tend to be rather well aware of their connections between their disciplines and other humanities and social sciences, although few possess enough disciplinary knowledge of STEM to engage its picture of reality, disciplinary problems, and cultural impacts with confidence. Among humanities scholars the issue seems not so much to be one of awareness but rather that the current academic climate does little to stimulate the sort of rigorous interdisciplinary expertise need to credibly engage the STEM and other humanities fields. Instead, the academic reward structure tends to favor those who do not stray too far from their disciplines. Faculty are hired into, tenured, and promoted primarily based on their abilities to teach somewhat well-defined disciplinary courses and the extent to which they address interesting problems of interest to members of their own discipline.

This is not to say there is anything wrong with rewarding good disciplinary work; it’s just that anyone who strays too far from their existing networks or support and base of expertise hazards their career in the present pressure-packed “publish or perish” and “get great letters of support” academic climate. Interdisciplinary work can also be extremely costly in effort and time since it requires practitioners to acquire expertise and remain current in multiple disciplines. Moreover, scholars working at disciplinary boundaries (like the history or philosophy of chemistry for example) are likely to find that their work is unlikely to be of broad enough interest to members of any particular discipline to secure publication in the best journals. A few fortunate and capable scholars may succeed in impacting both disciplines, but many are likely to find themselves confined to a sort of academic ghetto in which a marginalized community dialogues over issues largely of narrow interest while being largely ignored by the vast majority of practitioners in both disciplines.[28] Under such circumstances there is a strong temptation to let interdisciplinary work function as somewhat of a sideshow or hobby, something done by a few professionals but largely involving sporadic contributions by amateurs whose real work involves teaching or conducting research in their own disciplines.[29]

Given the amount of ground lost by the liberal arts in contemporary higher education it is perhaps too much to expect that the academic reward structure can be changed to accommodate significant interdisciplinary work between the sciences and humanities. Moreover, in the event such work could be accommodated or even stimulated by private funding sources, it is not necessary for the majority of scientists and humanities scholars to engage in significant scholarly work outside of their disciplines. Nevertheless, it is important for scientists and humanities scholars engaged in liberal arts education to have a nuanced and academically rigorous appreciation for the role their discipline plays in developing educated men and women who can critically engage and humanize the cultures of which they find themselves a part. What is needed are faculty in every discipline who can appropriately localize their disciplines within the liberal arts tradition, identify ways in which their discipline contributes to generally educated persons, and appropriately apply the insights, methods, and practices of other liberal arts fields to the practice of their discipline. In short, faculty members who teach and model what it means to be a liberally educated person.

What, then, does it mean to be a liberally educated person? Under current conceptions of the liberal arts there is some consensus that they do not just involve interdisicplinarity but also the cultivation of critical thinking, self-reflection and interpersonal skills – competencies that roughly correspond to the medieval trivium of grammar, rhetoric, and logic. Indeed, in general education schemes critical thinking and self-reflection are sometimes viewed as particularly the purview of philosophy and grammar, rhetoric, and interpersonal skills that of English and communication studies. However, all disciplines rely on these “general education” skills and philosophy, English, and communication studies not only cover significant aspects of what was once regarded as the preparatory trivium, they also function as means for interrogating reality and human experience in their own rights. In this sense, instead of viewing the humanities as a replacement for the trivium it might be better to localize both the humanities and sciences together in a reimagined quadrivium.

Indeed, traditional liberal arts interdisciplinarity is not merely interdisciplinarity for its own sake but a recognition that the liberal arts disciplines can together provide students with a fruitful means of interrogating and understanding reality. For example, the four disciplines of the medieval quadrivium all involved the use of mathematics to describe different aspects of reality and human experience. However, saying that the liberal arts are a fruitful means of understanding reality is not the same as saying that they have arrived at definitive answers to all questions or that there are no tensions at the interface between different disciplines. Rather, liberal arts interdisciplinarity acknowledges that different disciplines can work together using different methods and viewpoints to fruitfully probe different aspects of reality and human experience. The physical sciences, for example, combine logic and reason with a close experimental reading of the physical properties of the cosmos to construct a compelling picture of physical reality. They do not, however, address issues of meaning, purpose, what it means to live a good life, or even why the cosmos is orderly and intelligible. Such issues are more fitting for philosophers,[30] whose own answers should nonetheless be in some sense consistent with science's picture of reality if they are to be accepted as credible. Thus, in a reimagined quadrivium, STEM majors could be encouraged to partner with the humanities to better understand the context for their disciplinary work and develop resources for addressing life's deepest questions. In turn, humanities majors can be encouraged to take scientific insights seriously in their disciplinary work, secure in the knowledge that that their own insights are respected and that they need not make their disciplines "scientific" in order to somehow render them respectable.

Faculty who obtained their positions based on narrow disciplinary expertise are unlikely to find themselves well-equipped to draw connections between their disciplines and other areas of human knowledge. It is unlikely that there is any simple way to rectify this; however, one place to start might be to encourage faculty to think about how they might present their own disciplines in ways that maintain its integrity while promoting liberal arts ideals. Thus this essay will close with a few suggestions for how this might be done in my own discipline of chemistry. In doing so, I shall also attempt to demonstrate how the methods, aims, and needs of the sciences are not as disparate from those of the humanities as is often popularly supposed.

Science Reinforcing the Triviuum:

The Example of Grammar, Rhetoric, and Logic in Chemical Education

The medieval trivium included instruction in logic, grammar, and rhetoric, all of which were regarded as preparatory for more advanced study in the quadrivium and learned professions. Sometimes the trivium is thought to be associated with the literary as opposed to the mathematical arts of the quadrivium. However, since the logical and rhetorical training of the lower (*i.e.* trivial) trivium were regarded as preparatory to study of the quadrivium a better approach might be to regard the trivium as training in good thinking and communication. In effect, the trivium provided a foundation that enabled students to engage with the more mathematical logic of the quadrivium. For this reasons the STEM disciplines are more akin to the quadrivium, although they provide numerous opportunities to reinforce and affirm the lessons of the trivium. In fact, the practice of scientific inquiry is in many respects more akin to the medieval trivium in its aims and methods, specifically:

- The application of reason and experience within a community of practice to make sense of the physical and material reality; in fact the sciences were at various times considered to be a "natural philosophy" and exercise in interpreting the "book of nature."
- The use of symbols and mathematical models to describe, manipulate, and draw out the implications of scientific ideas and findings.
- The purposeful employment of rhetoric in various genres (scientific papers, talks, posters, proposals, *etc*…) to inform (teach), argue for (persuade), and memorably impart insight (delight) when communicating about scientific work.[31]

Unfortunately, even a cursory comparison between the practice of science and the way the sciences are usually taught reveals that the humanities are not the only ones who have abandoned important features of the liberal arts tradition. In fact, one of the reasons it is so easy to dismiss the STEM fields as liberal arts is that the aims and methods of science are not often made explicit when these fields are taught. For instance, technical writing is often approached as an exercise of placing the right content in the tightly-defined sections of a lab report in a sort of paint by numbers approach. This enables students to write something resembling a scientific article but doesn't really encourage students to think of their reports as a means of communicating scientific work, especially when they are encouraged to incorporate an extended theory section and extensive calculations that demonstrate their mastery of lecture material rather than their ability to understand their work deeply enough to effectively communicate it to an audience. In effect, the scientific article is reduced to an inauthentic academic exercise that is particularly susceptible to the sort of academic gamesmanship that prevents genuine learning.[32] More importantly, however, such an approach to science writing obscures the tightly-structured rhetorical form of the journal article, in which separate and somewhat freestanding sections are used to introduce the problems addressed by the work in their broader context, provide readers with insight into the experimental strategy employed, detail the work performed, present the resulting findings, and contextualize them in their broader significance.[33] In contrast, authentic journal article style lab reports require students to use theory and other background material to properly contextualize, describe, and discuss their work; to exercise moral courage in the excising of unnecessary theory; and to exercise good judgment and empathy in order to effectively craft each section to meet the needs of an imagined scientific reader. In short, they encourage students to view their work as contributing to a scientific conversation and apply their understanding of science and human nature to carry out that conversation effectively.

Overall, STEM education typically does a good job teaching students how to use symbols and mathematical models to more effectively solve scientific problems. This is particularly apparent in chemistry, which liberally employs a host of mathematical techniques, symbolic and logical systems (chemical formulas, electron pushing formalisms, *etc*…), and bonding models (Lewis, Valence Bond, MO Theory, etc…) to address chemical problems. However, the role of these models as means for applying thermodynamic and quantum mechanical insights to chemical systems is not always appreciated, particularly by beginning students. This is because students, teachers, and philosophers of science sometimes approach the "grammar" of chemistry as a mere conventional formalism rather than as an effort to develop working insight into the nature of matter and its properties. Although textbooks have yet to catch up, recent work in the history and philosophy of chemistry has illuminated many of these issues and provides ample resources for any liberal arts educator who wishes to present chemical symbols and models in a way that provides their students with insight into their distinctive character and role in chemical problem solving.[34]

A cursory examination of typical biology, chemistry, and physics textbooks and lab manuals, for instance, reveals that at the undergraduate level these sciences are usually taught as a body of established facts, theories, and methods. This can be well and good in that it enables students to more quickly become acquainted with the state of knowledge in these fields. However, students who learn science this way can find it difficult to appreciate the intellectual achievements to which they are heirs or to see themselves as participants in the scientific enterprise. The physicist Carl Weiman is fond of noting that while the largely unstructured program of physics graduate education is effective at producing genuine scientific colleagues; traditional approaches to undergraduate education tend only to help students learn scientific concepts, and they are marginally effective at that.[35]

Weiman himself locates STEM education's shortcomings in the widespread employment of the traditional lecture format of instruction. According to his research, the lecture approach actually caused students to regress from higher-level "expert" thinking and trained them to think like authority-reliant novices.[36] Consequently, he urges the adoption of inquiry-based active learning methods that in some sense replicate the process of scientific inquiry. Other researchers claim that the issue is not lecturing *per se*, however, but rather the way lecturing is employed. [37] Issues of effective teaching aside, however, what is clear is that undergraduate STEM education doesn't always encourage the kind of reasoning expected from a liberal arts discipline and needed by practicing scientists.[38] Interestingly, the proposed cures all involve encouraging greater reflection and discussion in the classroom with the goal of improving students' mastery of content, not necessarily their critical reasoning skills.[39] If Weiman is right, however, the problem extends beyond content mastery and current efforts to develop active-learning or nontraditional lecture methods should be supplemented by high-impact practices like case studies, debates, and required undergraduate research experiences that require students to think like scientists.[40]

Science in a Re-envisioned Quadriviuum:
Chemistry as General Education and a Way of Thinking and Learning about Reality

Like the four mathematical sciences of the quadrivium, the STEM disciplines are important as means of encountering the world both in and of themselves and in relation to other ways of knowing. As the preeminent science of ordinary matter (as opposed to the dark matter and subatomic particles of the physicists), chemistry's products influence the culture and substance of the world around us, while its central theoretical paradigm, atomic-molecular theory, undergirds much of contemporary biology, materials science, and neuroscience. Richard Feynman, the 1965 Nobel Laureate in physics, graciously identified atomic-molecular theory as the "one sentence" he would pass onto a successor generation in the event all other scientific knowledge was destroyed.

> …what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling on being squeezed into one another. In that one

> sentence there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.[41]

Moreover, chemistry is itself an important part of mankind's intellectual heritage, something that all educated persons ought to know. The American chemist Linus Pauling famously remarked:

> Chemistry is wonderful! I feel sorry for people who don't know anything about chemistry. They are missing an important part of life, an important source of happiness, satisfying one's intellectual curiosity. The whole world is wonderful and chemistry is an important part of it.[42]

And Pauling ought to know, having won Nobel prizes for both his humanitarian peace activism and his research into the nature of the chemical bond. The latter is especially noteworthy as it illustrates chemistry's uniquely valuable approach to physical reality. In the 1930s it was not immediately apparent how the then-revolutionary insights of quantum physics applied to chemistry. In order to address this problem Pauling developed a "valence bond" approach to chemical structure and illustrated its usefulness through a series of papers and, ultimately, a groundbreaking textbook on *The Nature of the Chemical Bond*.[43] Interestingly, like its principal rival, Molecular Orbital Theory,[44] this approach is highly-approximate and inferential, as it rests on the use of hydrogen-like orbitals and their hybrids in place of exact solutions to the equation (Schrödinger equation) governing the behavior of wave-like electrons in molecules.[45] Moreover, Pauling even developed it into a form that could be easily combined with the empirically useful and simpler approaches of G.N.Lewis and Irving Langmuir and combined with Keith Ingold's insights into the structure and reactivity of organic compounds. In short, Pauling's approach to chemical bonding was an act not merely of insight but of creativity – and an effective one at that; to this day it continues to serve as most chemists' working model for chemical reactivity, and is taught as such in general, organic, and biochemistry.

Yet Pauling's approach is only one of many approximate and often complementary methods that chemists have devised to handle the complex and often messy world of chemical compounds and their properties and reactivity. These include (but are hardly limited to) a plethora of acid-base definitions, electronegativity concepts, solid state bonding models, and approaches to reactivity (collision theory, transition state theory), about which it might reasonably be said that the issue is not one of "which is right, but which is most convenient to use in a particular situation."[46] Chemistry, like other sciences, has developed unique and uniquely valuable approaches for addressing the types of problems with which it is concerned. As such it is an important part of mankind's intellectual heritage, a way of thinking about reality that all educated persons could benefit from reflecting on. Unfortunately, however, most chemistry students are currently taught these approaches independent of their context – tools for solving "certain kinds" of problems in certain areas of chemistry, rather than a suite of intellectual tools that can be drawn from, added to, or improved as necessary. In other words, the distinctive approaches used by chemists are taught in a way that prevents students from viewing chemistry as a deeply insightful intellectual enterprise that they can learn from and contribute their own ingenuity towards advancing. Active learning exercises could potentially go a long way towards helping to remedy this situation; however, by and large the current implementations of these methods seem aimed at teaching chemical concepts more effectively, not teaching students how to think like chemists more effectively.[47]

A "facts and tools" based approach to chemical education can also make it difficult for students to localize science and its picture of the world in the totality of human knowledge and experience. In part this is a concomitant of chemistry's approach to the world; in using approximate by intuitively useful methods to solve problems, chemists have to some extent abandoned the search for ultimate nature of physical reality to the physics. This is not in itself deplorable, but it ignores the challenging questions raised by chemistry's picture of the world. If chemistry involves reading the book of matter, then matter is a book that presents many challenges of interpretation. These challenges are well-illustrated by chemistry's central theoretical paradigm, atomic molecular theory. In antiquity the idea that matter was comprised of atoms was tightly associated with issues of "chance and necessity", meaning, and purpose in the universe.[48] Indeed, it was popularly associated with Epicurus' ateleological view of the cosmos; thus its rehabilitation by the Renaissance humanists like Pierre Gassendi centered on recasting atoms as consistent with Divine providence.[49] Later thinkers like Robert Boyle, Isaac Newton, Roger Boscovitch, Joseph Priestley, John Dalton, and Joseph Proust repeatedly reconceptualized atoms on the basis of their own philosophical and theological interests.[50] However, the interplay of chance and necessity remains a thorny one. Though their proposals are marred by logical and historical difficulties, the late 19th Century physicist John Tyndall invoked Epicurean atomism when attempting to portray science and religion as necessarily in conflict,[51] an reprised in the last few years by the physicist Victor Stenger.[52]

The practice of chemistry also raises enormous questions about the harms and benefits of technology in the world and the social responsibilities of scientists. DDT well-illustrates the Janus-faced nature of chemistry; its status changed from that of a malaria-eradicating "miracle chemical" to environmental "bad-boy" in just a few short years following Rachel Carlson's publication of *Silent Spring*.[53] Nevertheless, the pharmaceutical industry may be more representative of chemistry's true potential for harms and benefits. Its net effect has been an overwhelming boon; antibiotics alone have led to a 2-10 year net increase in human life expectancy[54] while the development of psychotropic medications (like Thorazine/chlorpromazine) provided needed options for the treatment of mental health.[55] However, while the industry has behaved much more responsibly that popular perceptions of "big pharma" would suggest, its success and power raises a host of issues related to the cost, benefits, and influence of pharmaceuticals.[56]

All this is not to say that STEM educators themselves should teach their students about the philosophical, social, and ethical issues raised by their discipline's explanatory success, picture of reality, and technological outputs.[57] Such issues lie outside the bounds of science and it is perhaps unreasonable to expect that STEM educators will have either the time or ability to treat these issues adequately. However, students should at least be made aware that such issues exist[58] and should be encouraged to look to the humanities for resources that might help their efforts to grapple with them.[59] At minimum STEM professionals should communicate that their disciplines do not function in a vacuum and that STEM professionals, like other educated persons, have to confront the implications of their work and act responsibly in society.[60] Indeed, the sciences would be well-advised to adopt an ethic of "due care" similar to that utilized in engineering, as well as to follow the engineering disciplines by including minimal ethical training in their curricula.[61] Indeed, one issue that science education tends to leave to other disciplines is the business of living well, the subject of the next section.

Science Promoting the Good Life for All:
The Curious Example of "Better Things for Better Living through Chemistry"

Of course the STEM disciplines themselves do not ignore questions of right living; most STEM professionals tend to think of themselves as engaged in worthwhile work[62] and today virtually every STEM endeavor tends to be justified on the basis of its potential social benefits. Indeed, one of the two main merit criteria for the federal funding of scientific work is its potential for positive "broader impacts." Indeed, the STEM fields have a rich history of benefiting society through technological advances. Despite the occurrence of unintended consequences and harms, few would willingly return to a world without vaccines, antibiotics, electricity, construction equipment, and the printing press.

If the STEM fields are a source of benefit then it would stand to reason that STEM professionals bear some responsibility for considering exactly how the technological and knowledge outputs of their work might benefit society and the best way those benefits ought to be introduced or deployed. In short, the STEM fields themselves might benefit from the Renaissance humanist vision of the liberal arts as a means of promoting civilization and culture.[63] Moreover, the STEM fields will need the partnership of the humanities in this endeavor; although scientific and technological advances have been overwhelmingly beneficial, they do not address questions of meaning, purpose, joy, and satisfaction and have not brought mankind to the good life in any real sense. Ironically, this can sometimes be especially true for STEM professionals themselves, who endure the same pressures and are subject to the same vices as others and for whom a high-paying and relatively secure job often means extremely long work hours and stiff competition for resources. In fact, this often begins in graduate school as students commonly struggle with the workload and commitment needed for success in academia; sadly, a large proportion opt not to pursue life in academia after deciding that the good life is incompatible with the lifestyle of a typical STEM academic.[64] While it is encouraging to see STEM students engaging in the self-reflection about the good life and exercising the moral courage to go against what they perceive to be the norms of their fields, it bodes ill for the STEM disciplines as a whole if the very educators who are tasked with modelling the scientific “good life” to students are living lives that communicate a rather restrictive view of STEM as a vocation.[65]

Exactly why so many academics live lives that their students do not view as “good” bears some examination. There are of course counterexamples; for example my own doctoral advisor allowed (but did not encourage) students to work a forty hour workweek while my postdoctoral advisor was an excellent example of a joy-filled and humane life in science. Moreover, from a liberal arts point of view the issue isn’t so much that STEM academics choose to devote long hours to science. A consciously chosen academic asceticism can be part of a good life; indeed, it has been offered as one way that academics can avoid egoistic individualism and seek the common good.[66] Based on my personal experience, however, I strongly suspect most contemporary cases of scientific workaholism do not stem from such noble motives or even conscious motives at all.[67] Sometimes, it is borne of a passion and a genuine love for science and scientific work. In these cases, the danger stems not so much from the faculty member’s own lifestyle but from a failure to properly educate students; the faculty member unconsciously communicates that a similar level of passion and work intensity is an inalienable concomitant of successful scientific career. This can be compounded by the external pressures young scientists face as they compete for scarce academic jobs and grants, seek to win tenure, and otherwise appropriately advance in their careers. In other cases, however, faculty members' motives come not from joy but result from buckling under the pressures of the "business of science," a move in which scientists settle for something less than what they truly believe is the good life, a phenomena the biochemist Walter Hearn describes as whole people settling for half-truths.[68]

Regardless of motives, however, STEM professionals and their students could benefit from the liberal arts tradition of self-reflection, if for no other reason than to provide them with the opportunity to better make conscious reasoned decisions about the manner in which they choose to live out their scientific vocations; in short, to help them avoid simply drifting with the currents of their instincts and the social pressure around them and, in doing so, to better function as humane and responsible individuals.

Notes

[1] Vicki L. Baker, Roger G. Baldwin, and Sumedha Makker, "Where Are They Now? Revisiting Breneman's Study of Liberal Arts Colleges," *Liberal Education* 98, no. 3 (2012), http://www.aacu.org/publications-research/periodicals/where-are-they-now-revisiting-brenemans-study-liberal-arts; David W. Breneman, "Are We Losing Our Liberal Arts Colleges?," *American Association for Higher Education Bulletin* 42, no. 3 (1990).
[2] Tamar Lewin, "As Interest Fades in the Humanities, Colleges Worry," *The New York Times*, October 31, 2013 2013.
[3] Kevin Kiley, "Another Liberal Arts Critic," *Inside Higher Ed*(2013), https://www.insidehighered.com/news/2013/01/30/north-carolina-governor-joins-chorus-republicans-critical-liberal-arts.
[4] Debra Humphreys and Patrick Kelly, "How Liberal Arts and Sciences Majors Fare in Employment," (Washington, DC: Association of American Colleges and Universities, 2014); Hart Research Associates, "It Takes More Than a Major: Employer Priorities for College Learning and Student Success," (Washington, DC2013).
[5] In this respect it is interesting to note that while STEM-majors commonly take major-level humanities classes, most humanities majors typically take special non-majors STEM classes. Moreover, an unfortunate number of humanities scholars are willing to hold individuals as broadly educated even if they only have a cursory understanding of science and technology. One of my colleagues, himself a friend of the liberal arts, is fond of saying about the humanities "we've taken upper division classes in your disciplines; you haven't even taken the introductory classes in ours."
[6] Edward Grant, *The Foundations of Modern Science in the Middle Ages : Their Religious, Institutional, and Intellectual Contexts*, Cambridge History of Science (Cambridge ; New York: Cambridge University Press, 1996); *The Nature of Natural Philosophy in the Late Middle Ages*, Studies in Philosophy and the History of Philosophy (Washington, D.C.: Catholic University of America Press, 2010); David C. Lindberg, *The Beginnings of Western Science : The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450*, 2nd ed. (Chicago: University of Chicago Press, 2007); Edward Grant, *A Source Book in Medieval Science*, Source Books in the History of the Sciences (Cambridge, Mass.: Harvard University Press, 1974).
[7] The connections between the historical approaches of what are now regarded as humanities and contemporary science are illustrated in detail by Rens Bod, *A New History of the Humanities : The Search for Principles and Patterns from Antiquity to the Present* (Oxford University Press, 2013). Bod aims to show the importance of the humanities approaches for other fields of inquiry, most notably the sciences. In this essay I will show my qualified appreciation for Bod's work by offering his insights about the similarity between scientific and humanities approaches as an argument that both are equally worthy for consideration as liberal arts and for serving to humanize students through education. Indeed, part of the aim of this essay is to argue that the conventional humanities and sciences should work together more closely to fulfil this role, although in doing so each should be careful to accord adequate respect for each other's disciplinary expertise.
[8] H. I. Marrou, *A History of Education in Antiquity*, Wisconsin Studies in Classics (Madison, Wis.: University of Wisconsin Press, 1982).
[9] Note that in making this claim I do not allege that classical or medieval education actually achieved the ideals I am describing. Indeed, in many respects the classical and medieval liberal arts functioned much as K-12 schools in the US do today. They provided a primary education (trivium) which was followed by education in the things that educated persons ought to know (middle-high school). According to the historian of science David Lindberg neither included significant instruction in what would now be considered science. See David C. Lindberg, *The Beginnings of Western Science : The*

European Scientific Tradition in Philosophical, Religious, and Institutional Context, 600 B.C. To A.D. 1450 (Chicago: University of Chicago Press, 1992).

[10] For instance, metallurgists and the more sober alchemists employed some variant of Aristotelean matter theory. See Lawrence Principe, *The Secrets of Alchemy*, Synthesis (Chicago ; London: University of Chicago Press, 2013). David C. Lindberg, *Science in the Middle Ages*, The Chicago History of Science and Medicine (Chicago: University of Chicago Press, 1978); Edward Grant, *Physical Science in the Middle Ages*, History of Science (Cambridge ; New York: Cambridge University Press, 1977); *The Nature of Natural Philosophy in the Late Middle Ages*; Lindberg, *The Beginnings of Western Science : The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450*; Grant, *The Foundations of Modern Science in the Middle Ages : Their Religious, Institutional, and Intellectual Contexts*; Stephen Toulmin and June Goodfield, *The Architecture of Matter*, 1st ed. (New York,: Harper & Row, 1962).

[11] See, for example Antonia LoLordo, *Pierre Gassendi and the Birth of Early Modern Philosophy* (New York: Cambridge University Press, 2007); Saul Fisher, *Pierre Gassendi's Philosophy and Science : Atomism for Empiricists*, Brill's Studies in Intellectual History, (Leiden ; Boston: Brill, 2005); Lynn Sumida Joy, *Gassendi, the Atomist : Advocate of History in an Age of Science*, Ideas in Context (Cambridge Cambridgeshire ; New York: Cambridge University Press, 1987).

[12] Before that prospective natural scientists could learn by working with a master, much as science graduate students do today, although the process was much less formal than it is today. For example, Kepler worked for a time under Tycho Brahe while Michael Faraday got his start at the Royal Institution as an assistant to the chemist Humphry Davy.

[13] For a description of some of the factors which drove this transformation at Harvard see Stephen M. Contakes and Christopher Kyle, "Josiah Parsons Cooke Jr.: Epistemology in the Service of Science, Pedagogy, and Natural Theology," *Hyle – International Journal for the Philosophy of Chemistry* 17, no. 1 (2011).

[14] In this respect it should be noted Harvard's Chemist-president who spearheaded that college's transition to an elective system which would allow for specialized science education later become known as the compiler of the Harvard classics series of books.

[15] This trend continues today. In disciplines amenable to both social science approaches and traditional humanities approaches the practitioners of the latter are looked down upon by the former.

[16] These would of course object by claiming that the sciences too are subjective. There is some truth to this but this idea should not be taken too far. Nature is a universally-accepted text and all members of cultures are subject to its regularities. Moreover, although science primarily takes place in highly-industrialized wealthy societies scientists from difference nations and cultures use the same concepts and ideas when thinking and writing about science, collaborating with one another, and evaluating each other's work.

[17] Science students can even be asked to specialize at the undergraduate level. For example, at my institution chemistry majors have the option of completing a "general track" or "professional track" program as well as specialized tracks biochemistry, chemical physics, or chemical education. These involve less chemistry and much more biology, math and physics, and education courses, respectively. In fact, the biochemistry track majors are sometimes so weak in mathematics that they cannot understand the quantum mechanics used by the chemical physics track majors. Conversely, the chemical physicists are often completely ignorant of biochemistry and possess only a cursory understanding of organic chemistry. Thus while the chemical physics students are well equipped for graduate study in physics or physical chemistry they are often ineligible for further study in organic or biochemistry while biochemistry track majors are well prepared for medical school and graduate work in biochemistry but typically ineligible for graduate work in physical chemistry, at least without additional coursework.

[18] For an up to date if biased commentary see Alan D. Sokal, *Beyond the Hoax : Science, Philosophy and Culture* (Oxford ; New York: Oxford University Press, 2008).

[19] George Bugliarello, "A New Trivium and Quadrivium," *Bulletin of Science, Technology & Society* 23, no. 2 (2003): 108. Bugliarelo seems to refer to the Renaissance humanists' idea that classical learning should be used to inspire, guide, and otherwise humanize societies.

[20] Stanley Fish, "Will the Humanities Save Us?," *The New York Times*(2008), fish.blogs.nytimes.com/2008/01/06/will-the-humanities-save-us/.

[21] "The Uses of the Humanities, Part Two," *The New York Times*(2008), http://fish.blogs.nytimes.com/2008/01/13/the-uses-of-the-humanities-part-two/.

[22] I can see no reason why he is not, other than perhaps that perhaps Stanley Fish and his contemporaries have been accustomed to think about literary texts as something other than humanizing. I must admit, however, that as a STEM scholar at a Christian institution I to some extent welcome Fish's assertion. The early church which brought the Christian gospel to the ancient world would doubtless have agreed in the limited ability of ancient literary and philosophical achievements to change lives, even though they by and large welcomed the genuine insights of pagan learning.

[23] I do not have the expertise to argue about this one way or the other but since I suspect the Fish is correct this is one reason why I am not advocating that the humanities return to some sort of great books program. For a contrary view from someone who largely agrees with the analysis of the humanities presented in this paper see Anthony T. Kronman, *Education's End : Why Our Colleges and Universities Have Given up on the Meaning of Life* (New Haven: Yale University Press, 2007).

[24] Steven Pinker, "Science Is Not Your Enemy: An Impassioned Plea to Neglected Novelists, Embattled Professors, and Tenure-Less Historians," *The New Republic*(2013), http://www.newrepublic.com/article/114127/science-not-enemy-humanities.

[25] Nevertheless, in crafting his essay Pinker had portrayed the issue as one of the humanities rejecting science and his resulting exchange with the writer Leon Wieseltier focused narrowly on science's role as a purveyor of knowledge. See Leon Wieseltier, "Crimes against Humanities Now Science Wants to Invade the Liberal Arts. Don't Let It Happen.," ibid., http://www.newrepublic.com/article/114548/leon-wieseltier-responds-steven-pinkers-scientism. Steven Pinker and Leon Wieseltier, "Science Vs. The Humanities, Round III," ibid., http://www.newrepublic.com/article/114754/steven-pinker-leon-wieseltier-debate-science-vs-humanities.

[26] To cite one, in arguing that scientific pictures of origins falsify every religious origins account Pinker appears to treat these accounts as examples of modern historiography and does scant justice to these accounts as ancient religious texts. However, my point here is not to argue for or against the ultimate claims of the New Atheists but rather to point out that deficiencies in their work can be traced to a failure to take the humanities seriously. Indeed, this has bene ably pointed out by both religious and skeptical critics of the New atheism. See, for example, Alister E. McGrath, *Why God Won't Go Away : Is the New Atheism Running on Empty?* (Nashville: Thomas Nelson, 2010); Alister E. McGrath and Joanna McGrath, *The Dawkins Delusion : Atheist Fundamentalism and the Denial of the Divine* (Downers Grove, Ill.: InterVarsity Press, 2007); David Bentley Hart, *Atheist Delusions : The Christian Revolution and Its Fashionable Enemies* (New Haven: Yale University Press, 2009); Michael Ruse, *Science and Spirituality : Making Room for Faith in the Age of Science* (Cambridge England ; New York: Cambridge University Press, 2010).

[27] This is also not to say that the medieval and Renaissance liberal arts were actually taught in a coherent manner as much a recognition that experts in each discipline were expected to be conversant with other disciplines and use their insights and methods appropriately. Indeed, it is not entirely clear that the ideals of Renaissance humanism made a tremendous impact on education. See for example Robert Black, *Humanism and Education in Medieval and Renaissance Italy : Tradition and Innovation in Latin Schools from the Twelfth to the Fifteenth Century* (Cambridge, UK ; New York: Cambridge University Press, 2001).

[28] This is true, for example, of work in the history of chemistry and the philosophy of chemistry; although the former has received significant support from industrialists and is supported by the chemical heritage foundation, most chemists regard it as little more than an interesting hobby. The latter has spurred significant publications from academic presses but is hasn't yet made a significant impact on the philosophy of science proper, let alone philosophy as a whole. The philosophy of biology field has had a somewhat wider impact due to the large amount of public interest surrounding issues of evolution and in my opinion the skeptical philosopher of biology Michael Ruse has produced some of the most balanced, thoughtful, and intellectually rigorous contributions to the American evolution wars; however, unlike many individuals publishing in this area he has yet to be rewarded with a spot on the New York Times bestseller list.

[29] Here I speak from experience since my own work in the philosophy of chemistry and science and religion fields is of this sort.

[30] In my own context at a religious institution I would add theology as an appropriate resource as well.

[31] This division reflects the three functions of rhetoric that St. Augustine of Hippo attributed to Cicero. See Augustine of Hippo *De Doctrina Christiana* IV.XII.

[32] For example, science students are often unwittingly taught to eschew pursuing good science communication in favor of a "knowledge and data dump" approach. The latter is more likely to lead to them getting full points for their report since the aim of the report is for them to demonstrate their knowledge of the concepts behind the experiment directly, not communicate their work effectively using their knowledge. This might be appropriate for beginning students who have little experience writing about science at all; however it is hardly suitable as a general method for educating thinking STEM professionals.

[33] This form is sometimes described graphically as an IMRD hourglass in which a broad Introduction section orients the reader, getting them ready to appreciate the specific experimental and computational Methods employed, understand the Results, and appreciate a Discussion of their broader significance. See Susan S. Hill, Betty F. Soppelsa, and Gregory K. West, "Teaching Esl Students to Read and Write Experimental-Research Papers," *TESOL Quarterly* 16, no. 3 (1982); Marin S. Robinson and Fredricka A. Stoller, *Write Like a Chemist: A Guide and Resource* (Oxford ; New York: Oxford University Press, 2008).

[34] Some examples include Kōstas Gavroglou and Ana Simões, *Neither Physics nor Chemistry : A History of Quantum Chemistry*, Transformations : Studies in the History of Science and Technology (Cambridge, Mass.: MIT Press, 2012). Kostas Gavroglu and Ana Simões, "From Physical Chemistry to Quantum Chemistry: How Chemists Dealt with Mathematics," *Hyle – International Journal for the Philosophy of Chemistry* 18, no. 1 (2012). Davis Baird, Eric R. Scerri, and Lee C. McIntyre, *Philosophy of Chemistry : Synthesis of a New Discipline*, Boston Studies in the Philosophy of Science, (Dordrecht: Springer, 2006). E. R. Scerri, "Has Chemistry Been at Least Approximately Reduced to Quantum Mechanics?," *Proceedings of the Biennial Meeting of the Philosophy of Science Association* 1(1994). J. van Brakel, *Philosophy of Chemistry : Between the Manifest and the Scientific Image*, Louvain Philosophical Studies (Leuven: Leuven University Press, 2000).

[35] Carl Wieman, "Why Not Try a Scientific Approach to Science Education?," *Change*, no. September-October (2007), www.changemag.org/Archives/Back Issues/September-October 2007/full-scientific-approach.html.

[36] Roughly, expert level knowledge is characterized by pattern recognition and self-assessment while novice thinking is characterized by memorization, a reliance on authorities, and an inability to deviate from rigid algorithms. For a more extensive description of the differences between expert and novice thinking see John Bransford, Ann L. Brown, and Rodney

R. Cocking, *How People Learn: Brain, Mind, Experience, and School, Expanded Edition*, Expanded ed. (Washington, D.C.: National Academy Press, 2000), 31-50.

[37] Matthew T. Hora, "Limitations in Experimental Design Mean That the Jury Is Still out on Lecturing," *Proceedings of the National Academy of Sciences* 111, no. 30 (2014). Note that Hora's thesis has been called into question. See Scott Freeman et al., "Reply to Hora: Meta-Analytic Techniques Are Designed to Accommodate Variation in Implementation," ibid.

[38] In some respects the undergraduate STEM approach to critical thinking is one of admitting good critical thinkers and letting them do their thing.

[39] These include inquiry-based learning, Process Oriented Guided Inquiry Learning (POGIL), case studies, and the use of flipping to encourage more active work in the classroom. In all these the goal, however, is to make the transmission of content more effective, not necessarily to engage students in the practice of scientific inquiry. Even Wieman argues for active learning on the grounds that it leads to greater mastery of scientific concepts, not because it produces better scientific thinkers.

[40] Other strategies that have been shown effective in encouraging critical thinking include service learning, debates, simulations, and real-world problem solving tasks. See Canter for Assessment and Improvement of Learning, "Cat: Critical Thinking Assesssment Test Training Manual, Version 8," ed. Tennessee Tech University (Tennessee Tech University, 2013), 21-23.

[41] Richard P. Feynman, Robert B. Leighton, and Matthew L. Sands, *The Feynman Lectures on Physics*, 3 vols. (Reading, Mass.,: Addison-Wesley Pub. Co., 1963), volume 1, lecture 1, 1-2.

[42] Linus Pauling, *The Development of the Concept of Chemical Bond*, *Hitchcock Foundation Lectures, The University of California-Berkeley* (Linus Pauling and the Nature of the Chemical Bond: A Documentary History: Special Collections & Archives Research Center, The Valley Library, Oregon State University, 1983), Audio recording.

[43] *The Nature of the Chemical Bond and the Structure of Molecules and Crystals; an Introduction to Modern Structural Chemistry*, The George Fisher Baker Non-Resident Lectureship in Chemistry at Cornell University (Ithaca, N.Y., London,: Cornell University Press;
H. Milford, Oxford University Press, 1939).

[44] Although they at times functioned as rivals, valence bond and molecular orbital theory are perhaps best thought of as complementary. In fact, their pictures of bonding converge when fewer computation-simplifying approximations are employed.

[45] It also ignores the influence of electrons' specific positions on the positions of other electrons, a problem termed electron-electron correlation (specifically dynamic correlation).

[46] James Huheey used this terminology to refer to different acid-base concepts. See James E. Huheey, Ellen A. Keiter, and Richard L. Keiter, *Inorganic Chemistry : Principles of Structure and Reactivity*, 4th ed. (New York, NY: HarperCollins College Publishers, 1993), 318.

[47] This is not to say those faculty who employ active learning do not intend to help their students think like scientists, not is it saying that active learning strategies have no benefit in this regard. However, the stated aims and justifications used for such methods is almost exclusively focused on improving students' masters of course content (*i.e.* scientific concepts) not developing students' abilities to think like scientists.

[48] See Leucippus, Democritus, and Taylor (translator), *The Atomists, Leucippus and Democritus : Fragments : A Text and Translation with a Commentary*, fr. 34.30 Arrighetti, 153; Pullman, *The Atom in the History of Human Thought*, 34-35; Furley, *The Greek Cosmologists Volume 1: The Formation of Atomic Theory and Its Earliest Critics*, 146-51. Nowadays the interplay of "chance and necessity" is often associated with biology, at least since Jacques Monod authored his famous monograph of that name. Jacques Monod, *Chance and Necessity; an Essay on the Natural Philosophy of Modern Biology* (New York,: Vintage Books, 1972).

[49] The rehabilitation of atomism is admirably treated by the sources listed in note 11.

[50] For a brief overview of some of these efforts see John Henry, "Atomism," in *The History of Science and Religion in the Western Tradition: An Encyclopedia*, ed. G.B. Ferngren, E.J. Larson, and D.W. Amundsen (Garland, 2000). More detail can be found in Margaret J. Osler, *Divine Will and the Mechanical Philosophy : Gassendi and Descartes on Contingency and Necessity in the Created World* (Cambridge: Cambridge University Press, 2002). Margaret G. Cook, "Divine Artifice and Natural Mechanism: Robert Boyle's Mechanical Philosophy of Nature," *Osiris* 16(2001); H. R. Jacob, "Boyle's Atomism and the Restoration Assault on Pagan Naturalism," *Social Studies of Science* 8, no. 2 (1978). Arnold Thackray, *Atoms and Powers; an Essay on Newtonian Matter-Theory and the Development of Chemistry*, Harvard Monographs in the History of Science (Cambridge, Mass.,: Harvard University Press, 1970). Isabel Rivers and David L. Wykes, *Joseph Priestley, Scientist, Philosopher, and Theologian* (Oxford ; New York: Oxford University Press Inc., 2008).

[51] See Frank M. Turner, "Ancient Materialism and Modern Science: Lucretius among the Victorians," in *Contesting Cultural Authority : Essays in Victorian Intellectual Life* (Cambridge; New York, NY: Cambridge University Press, 1993). Although it was fashionable for a time in the late 19th and early 20th Century, historians do not currently consider this "conflict thesis" to be credible.

[52] Victor J. Stenger, *God and the Atom* (Amherst, New York: Prometheus Books, 2013). Like the works of other New atheists, Stenger's book illustrates the dangers of sloppy thinking about the humanities. Readers are invited to read Stenger's book alongside Bernard Pullman's *The Atom in the History of Human Thought* (Oxford University Press, 1998), which

though not itself without its deficiencies tries to adopt a properly nuanced view of the relationship between atomism and religious thought.

53 The following collection of original documents illuminates DDT's meteoric rise and downfall: Thomas R. Dunlap, *Ddt, Silent Spring, and the Rise of Environmentalism : Classic Texts*, Weyerhaeuser Environmental Classics (Seattle: University of Washington Press, 2008).

54 W. McDermott and D. E. Rogers, "Social Ramifications of Control of Microbial Disease," *Johns Hopkins Med J* 151, no. 6 (1982).

55 David Healy, *The Creation of Psychopharmacology* (Cambridge, MA: Harvard University Press, 2002).

56 For a sophisticated treatment of the standard issues see Michael A. Santoro and Thomas M. Gorrie, *Ethics and the Pharmaceutical Industry* (Cambridge: Cambridge University Press, 2007). Others include the use of cognitive enhancing drugs, medicalization, and the role of taxpayer-funded research in drug development. Henry T. Greely, "Some First Steps toward Responsible Use of Cognitive-Enhancing Drugs by the Healthy," *The American Journal of Bioethics* 13, no. 7 (2013).see Elizabeth A. Kitsis, "The Pharmaceutical Industry's Role in Defining Illness," *Virtual Mentor: American Medical Association Journal of Ethics* 13, no. 12 (2011). Merrill Goozner, *The the Truth Behind the Cost of New Drugs* (Berkeley: University of California Press, 2004).

57 This is not to say that technology follows science; in many historical cases it has been the other way around. However, contemporary technology is often driven by the underlying fundamental science.

58 At Westmont, for instance, all chemistry majors take a senior capstone dealing with issues of this sort.

59 In saying this I am not advocating that STEM students view the humanities merely as a repository of resources any more than I would encourage humanities majors to view the STEM fields as a source of technological benefits and harms; rather I am simply saying that there are resources within the humanities that STEM students should be made aware of and utilize.

60 A good example concerns scientists engaged in research with military implications. As discussed in my last CLA paper war-related science raises a host of difficult issues that scientists addressed in quite disparate ways, of which "issue avoidance" seemed to be the least helpful. See Stephen M. Contakes and Taylor Jashinsky, "Chemistry, Social Responsibility, and Modern Warfare," in *12th Annual Conference on the Liberal Arts* (Westmont College, Santa Barbara, CA2013). An updated copy is available on request.

61 The sciences have begun to make strides in this regard, at least since the NSF and NIH began to mandate ethical training for students involved in federally-funded research. Such training non-inappropriately focuses on the ethics of research conduct and the treatment of subjects and only rarely encourages the type of ethical reflection expected of liberal arts graduates in the humanities. and Institute of Medicine US National Academy of Sciences National Academy of Engineering, Committee on Science, Engineering, and Public Policy, *On Being a Scientist : Responsible Conduct in Research*, 3rd ed. (Washington, D.C.: National Academy Press, 2009). For an exception, see Gary Comstock, *Research Ethics : A Philosophical Guide to the Responsible Conduct of Research* (Cambridge ; New York: Cambridge University Press, 2012).

62 The historian of science Steven Shapin claims that STEM professionals seem to exhibit more genuine altruism than many humanities scholars in their pursuit of work they genuinely believe will benefit society. Steven Shapin, *The Scientific Life : A Moral History of a Late Modern Vocation* (Chicago: University of Chicago Press, 2008), 312. While I cannot comment on the motivations of humanities scholars, in my experience scientists genuinely want to benefit humanity through their work.

63 Although the Renaissance humanists primarily viewed the humanities as the means of civilizing students and promoting culture both the sciences and humanities have been historically considered important means for advancing civilization, as may be seen from the common view that literacy and technology are means of "liberating" human thought and "developing" societies.

64 See Jessica Lober Newsome, "The Chemistry Phd: The Impact on Women's Retention," (Royal Society of Chemistry and The UK Resource Centre for Women in Science, Engineeting, and Technology, 2008). In the spirit of full disclosure I must admit that I personally haven't always modeled a balanced lifestyle.

65 This is not to say that it is necessarily unhealthy to devote long hours to scientific work; STEM graduate students should possess a passion for their subjects and, like Newton, feel themselves to some extent children playing at the seashore of undiscovered truth. Nevertheless, this spirit is far removed from a view of science in which all other aspects of life are sacrificed. For an example of the sort of thinking I am referring to see "Reality Check," *Nature* 477, no. 7362 (2011). Although the sentiments in that article are far from universal the pressures of the highly-competitive funding strapped academic culture sometimes lead to an extreme workaholism that is not conducive to more holistic visions of the good life. For a good example of the sort of lifestyle to which I am referring see Heidi Ledford, "Work-Ethic: The 24/7 Lab," ibid.

66 John B. Bennett, *Academic Life : Hospitality, Ethics, and Spirituality* (Bolton, Mass.: Anker, 2003), 80-82.

67 Interestingly, Steven Shapin documents that early-modern scientists to some extent functioned that way. See Shapin, *The Scientific Life : A Moral History of a Late Modern Vocation*. Shapin's study is also remarkable in that he examines the role of particular "virtues" for scientific success, although he focuses on what he calls technoscience, or science performed with the aim of pursuing entrepreneurial technological developments. Indeed, I must admit that there were times I wondered about whether some of the "virtues" he describes would be beneficial for other kinds of scientific work.

68 Walter R. Hearn, "Whole People and Half-Truths," in *The Scientist and Ethical Decision*, ed. Charles Hatfield (Downers Grove, IL: InterVarsity Press, 1973).