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EDITORIAL

Specialized Science

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As the body of scientific knowledge in a discipline increases, there is pressure for specialization. Fields spawn subfields that then become entities in themselves that promote further specialization. The process by which scientists join specialized groups has remarkable similarities to the guild system of the middle ages. The advantages of specialization of science include efficiency, the establishment of normative standards, and the potential for greater rigor in experimental research. However, specialization also carries risks of monopoly, monotony, and isolation. The current tendency to judge scientific work by the impact factor of the journal in which it is published may have roots in overspecialization, as scientists are less able to critically evaluate work outside their field than before. Scientists in particular define themselves through group identity and adopt practices that conform to the expectations and dynamics of such groups. As part of our continuing analysis of issues confronting contemporary science, we analyze the emergence and consequences of specialization in science, with a particular emphasis on microbiology, a field highly vulnerable to balkanization along microbial phylogenetic boundaries, and suggest that specialization carries significant costs. We propose measures to mitigate the detrimental effects of scientific specialism.

> **Every man gets a narrower and narrower field of knowledge in which he must be an expert in order to compete with other people. The specialist knows more and more about less and less and finally knows everything about nothing.**
>
> —Attributed to Konrad Lorenz

Science is a highly specialized enterprise. Science requires a specialized knowledge base and a specialized approach to problems. Accordingly, science is comprised of specialties and subspecialties that have evolved to define discrete fields of study. For a field, specialization can be viewed as a sign of success. As disciplines mature and expand their knowledge base, specialization becomes inevitable as the amount of information becomes too large for any individual scientist to master. The major specialties of science are physics, chemistry, and biology, each of which has spawned dozens of subspecialties ranging from astronomy to zoology. In the allied field of medicine, physicians long ago separated into surgeons and internists, each of which now includes over a dozen subspecialties. Surgeons specialize their skills primarily according to anatomical regions, as they are required to master increasingly challenging technical procedures. More recently, medicine has developed specialists in pediatrics, women's health, radiographic techniques, and mental disorders, to name a few. Specialization is rife throughout society. For example, lawyers specialize depending on the type of law they practice, police specialize depending on the duties they perform, and the armed forces now include many branches that specialize according to the type of warfare in which they engage. Specialization is generally viewed in a positive light because it permits expertise in a subset of knowledge in a discipline and is encountered in all areas of human endeavor in which complexity emerges. Specialization can produce organizations that define themselves through technological prowess or the excellence of their trade, and this can be a source of pride that provides self-definition to specialists. Specialization emerges and is maintained because it confers obvious benefits to those that specialize.

The advantages and disadvantages of specialization have been studied primarily in the context of economic theory, finding forceful exposition in Adam Smith's 1776 treatise *An Inquiry into the Nature and Causes of the Wealth of Nations* (1). Smith noted the advantages of a division of labor among workers to increase their efficiency and productivity. Specialization can extend to entire countries, which develop specialized economies centered on those areas in which they have advantages, providing the basis for globalization and world trade. However, despite its benefits to those who practice it and to those who are served by it, specialization has its costs. The guild system in Europe arose in the Middle Ages as artisans and merchants sought to maintain and protect specialized skills and trades. Although such guilds often produced highly trained and specialized individuals who perfected their trade through prolonged apprenticeships, they also encouraged conservatism and stifled innovation. Specialization in warfare has led to different services that compete for resources and prestige. Specialized services such as the Navy further subspecialize to create carrier, surface, submarine, and marine forces that may compete among themselves and fail to adapt to the changing nature of warfare. Interservice rivalry is a well-recognized problem in the military that can be detrimental to national interests. The United States Armed Forces require that officers rotate in other services prior to senior promotions in an effort to curb this problem (http://en.wikipedia.org/wiki/Interservice_rivalry). Hence, the benefits of specialization are tempered by the possibility that specialized groups become isolated, resist innovation, and engage in destruc-

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tive competitiveness. Economists now recognize that one of the principal costs of the division of labor is the cost of coordinating the efforts of highly specialized workers, something which becomes increasingly important as the number of specialties and specialists increases (2).

Science is a highly specialized human endeavor, but to our knowledge, the consequences of the divisions of labor found among scientists have not been examined systematically. Since its emergence as a distinct human activity during the scientific revolution, science has been enormously successful in explaining our world and in enabling technologies that have transformed the quality of human existence. From its beginnings in astrology, astronomy, alchemy, and classical medicine, science has generated a voluminous amount of information that has spawned the creation of dozens of disciplines that include microbiology and immunology, both of which provide the underpinnings for most, if not all, papers published in *Infection and Immunity* (IAI). In fact, *Infection and Immunity* covers only a relatively small subset of these disciplines, as evidenced by the fact that the American Society for Microbiology (ASM) publishes 12 other journals, each devoted to other subspecialties.

Both microbiology and immunology are themselves sectarian, and each is comprised of many subdisciplines. For microbiology, these are generally microbe based, with a subdiscipline centered on researchers interested in specific microbes such that even within the larger groupings of bacteriology, mycology, and parasitology, there are mycobacterial, staphylococcal, chlamydial, candidal, and malarial communities, among many others. These groups tend to attend meetings that focus on their favorite organisms and seldom interact collaboratively across microbial species. The immunological subdisciplines tend to focus on various components of the immune system, with adaptive (T and B cell), innate, and mucosal immunity constituting major affinity groups, and specialize in processes and functions of the immune system (3). Like the microbiologists, these constituencies are largely self-contained, although their boundaries are constantly challenged by the fact that the immune system is highly interconnected, rendering human-defined boundaries physiologically irrelevant when considering the system as a whole.

AN ECONOMIC VIEW OF SPECIALIZATION

In *An Inquiry into the Nature and Causes of the Wealth of Nations* (1), Smith promoted the view that specializing in certain types of labor, i.e., the division of labor, promotes efficiency and productivity by breaking down large jobs into smaller components that can be readily mastered by individuals, allowing the more rapid delivery of superior products. Smith famously used the example of a pin factory, in which the manufacturing process could be broken down into 18 discrete steps, each performed by a specialist. Through the division of labor, 10 workers could produce nearly 50,000 pins a day, whereas the same number of workers performing each step themselves could produce only 10 to 20 pins each day. Although scientific knowledge is quite different from a packet of pins, both have in common the delivery of goods, which for science consists of information, education, analysis, an improved understanding of the natural world, and the applications of that knowledge. Hence, the concepts developed from economics may have some relevance to analyzing the consequences of specialization in science. Like specialization in other fields of human endeavor, specialization in science has advantages and disadvantages. We will consider both and suggest strategies for maximizing advantages and minimizing disadvantages.

ADVANTAGES OF SPECIALIZATION IN SCIENCE

The advantages of specialization in science mirror those delineated by Smith for the division of labor, including efficiency, reduced time to production, improved quality, and the partitioning of vast quantities of knowledge into more-manageable units. In fact, there is no alternative to specialization in science, for the subject matter is so vast that progress requires a concentrated focus on a narrow problem for a protracted period of time. Consequently, scientific training has become highly specialized, with graduate programs channeling students into ever narrower areas.

Gaining recognition as a specialty or subspecialty can be important to establish legitimacy and to compete for resources. The medical subspecialty of infectious diseases originally arose from an increasing demand for expertise in the administration of antibiotics. The inaugural meeting of the Infectious Diseases Society of America (IDSA) took place in 1963 (4), and subspecialty board certification was first offered in 1972. However, demand and reimbursement for the expertise of infectious disease specialists was tenuous at first, leading the IDSA president to observe in 1978 that “I cannot conceive the need for 309 more infectious disease experts unless they spend their time culturing each other” (5). However, the subsequent emergence of the AIDS epidemic changed the equation, and today there are estimated to be 7,500 board-certified infectious disease specialists in the United States alone (6). The complexities associated with treating a chronic multiorgan disease have led to the further subspecialization of some infectious disease specialists into those who focus primarily on HIV, and this has led to the formation of the HIV Medicine Association (HIVMA), closely allied with IDSA. Hence, success, complexity, and need are powerful forces in promoting specialization.

Given the success of science in the past 2 centuries and the fact that this success has occurred in the setting of increasing specialization, it is likely that the process is beneficial to the enterprise. The advantages of reducing the amount of information that must be mastered by any individual are largely self-evident. Given that specialization will remain the status quo in the foreseeable future, we will devote more attention to the disadvantages, particularly as they apply to particular fields that contribute to *Infection and Immunity*.

DISADVANTAGES OF SPECIALIZATION IN SCIENCE

Some of the disadvantages of specialization in science also mirror the problems resulting from the division of labor in the economic sphere, including monotony, lack of mobility, monopoly, isolation, and the costs of coordination.

Monotony was a major problem in optimizing the efficiency of industrial production once individuals became dedicated to specific tasks. The extent to which monotony is a problem among scientists is unknown, but given human nature, it is likely that some scientists become disenchanted with their chosen areas of expertise and may wish to move to other pastures. The industrial solution to monotony involved rotating jobs, but that is not readily applicable to science, for the development of scientific expertise and the maintenance of specialized laboratories require enormous expenditures of personal and financial resources. Consequently, many scientists live and die in their chosen fields of expertise, for it is simply too difficult to change fields. Adding to the cost of changing fields is the fact that most scientists are identified with their fields and develop social connections accordingly. For example, an individual who has specialized in *Salmonella* pathogenesis or T cell function would have to make a major effort to change to work on cryptococcal pathogenesis or B cell function and vice versa, despite the fact that each of these specialties are subfields within the parent fields of microbiology and immunology, respectively. In fact, fields become social units that define norms and are essential for advancement. For example, funding proposals are reviewed by established members in a given field, and in a similar fashion, awards and honors are generally bestowed by those who constitute the "establishment" in a field. In this regard, acceptance into a field carries some of the benefits of the medieval guild system, whereby accepted scientists are considered experts and given considerably more latitude in their work than newcomers, especially if their contributions contribute to the status quo or reinforce prevailing paradigms in the field. Conversely, it is very difficult for newcomers to break into fields and achieve the acceptance accorded to longstanding members, especially if they bring new ideas that are contrary to the accepted views in that field. Hence, specialization in science has the immediate disadvantage for an individual that the chasm can be too deep for movement to another field and that the benefits of field membership are too great. Once an individual becomes established in a certain field, changing fields carries a disproportionate cost that results in a *de facto* lack of mobility for most scientists.

Is lack of scientific mobility good or bad for science? The fact that most scientists become wedded to their fields of study has the advantage of providing continuity and stability to their respective fields, including the maintenance of specialized knowledge and normative standards for research. However, these advantages carry potential disadvantages, since continuity and stability can also exclude new ideas and promote the phenomenon of groupthink, whereupon fields may stagnate. The ability of Louis Pasteur to radically transform the fields of microbiology and immunology has been attributed to his "outsider" status as a chemist and nonphysician taking a fresh look at infectious diseases and strategies for their prevention (7).

One paradox is that all fields want to be recognized outside their fields and most desire growth yet those desires are often thwarted by the same forces that bring cohesion to a field. For example, there is ample historical precedent that great progress can be made at the interface between fields, where each field can cross-fertilize the other, resulting in synergistic interactions. Unfortunately, scientists who strive to bridge two fields do so at their peril for they run the risk of being considered "other" and thus fail to accrue the benefits that come with field membership. This may be a hurdle for some contributors to *Infection and Immunity*, a journal with a strong emphasis on microbial virulence, a phenomenon that occurs only in a susceptible host and thus requires work at the interface of microbiology and immunology.

Monopoly is another potential disadvantage of specialization. In science, a monopoly can emerge with regard to information, access to reagents, access to facilities, or collaborative interactions. Specialization in an area can lead to the generation of unique reagents, such as certain microbial strains, transgenic mice, etc. Most journals, including *Infection and Immunity*, have strict policies requiring the sharing of reagents that are described in the "Instructions to Authors." However, not all individuals with unique reagents are free and generous with their distribution, which creates a situation akin to a monopoly. Monopolies can also arise in the context of working with dangerous microbes, such as those requiring biosafety level 3 (BSL3) or 4 containment. In those situations, the monopoly arises from the regulatory requirements that the experimental work be performed in containment facilities that are available only in certain institutions, thus constituting a scarce resource. Fields focused on research on microbes that require high containment define norms for publication that require work with the wild-type virulent strain and thus effectively exclude investigators that lack such facilities from entering the field. This exclusion can find many expressions. For example, in fields of research in which attenuated organisms that allow work with BSL2 containment exist, research papers involving such strains may find little acceptance by the established group, who demand validation of the data using fully virulent strains before accepting the findings. This, in turn, requires that any investigator who wishes to contribute to such a field must find the means to carry out experiments under conditions of high-level containment, often with the collaboration and to the benefit of established investigators who have a monopoly on production by virtue of access to the required facilities. Although clearly we are not advocating the relaxation of rules put in place to ensure the safety of investigators and the public, we merely use this example to point out that such rules may serve to create monopolies.

The mania around the impact factor that has proven so problematic in the biological sciences (8, 9) may have some of its roots in the increased specialization and intellectual isolation of working scientists. As scientists specialize, they tend to lose their capacity to critically evaluate the importance and quality of work in other areas of science and may increasingly look for surrogate markers. In this context, the journal impact factor has emerged as a means to judge the quality of individual research articles, in stark contrast to the impact factor's origin as a bibliographic tool to help librarians gauge the relative importance of journals (10). Consequently, many scientists have begun to judge the value of a scientific paper based on the venue in which it is published rather than on the importance, quality, and novelty of its content (11). This has introduced a major distortion in the practices of scientists as they seek to publish their work in higher-impact-factor journals that increasingly restrict publication (in order to maintain their high impact factors), thereby creating an environment conducive to questionable research practices (12, 13).

Given the enormity of scientific knowledge and the dispersed nature of the modern research enterprise, it is not surprising that the costs of coordinating specialized researchers can be substantial. A study of nearly 500 multi-institutional research projects supported by the National Science Foundation revealed an inverse relationship between the number of institutions involved and the achievement of project outcomes, suggesting that group heterogeneity reduced the efficiency of research when members belonged to different fields and/or institutions (14). Yet, as noted in numerous instances (examples provided below), the benefits of transdisciplinary research can be considerable once scientists leave their intellectual silos. Understanding a complex phenomenon typically requires a combination of approaches. Just as economists have documented the critical role of generalists on innovation teams (15), scientific leadership may benefit from individuals with broad vision and an ability to synthesize observations from diverse fields.

THE MICROBIAL ARCHIPELAGO

The problem of specialization is particularly acute in the field of microbiology. Microbiology is an unusual discipline in which scientists usually specialize by becoming experts on individual microbes. Many microbiologists begin and end their scientific lives working on the same organism and together with their colleagues form intellectual islands that, when considered in aggregate, constitute a microbial archipelago. Hence, specialization in microbiology results in fields that are delineated by phylogenetic boundaries. Medical microbiology has spawned bacteriology, mycology, parasitology, and virology, and as each field advances, each, too, spawns subdisciplines that can become fields unto themselves. For example, virology has become subdivided into positive- and negative-strand viruses, HIV, and DNA viruses. Similarly, most experimental bacteriologists, mycologists, and parasitologists remain focused on single organisms, often for their entire careers. This translates into a preference for scientific meetings that focus on the organism of interest and has resulted in a proliferation of single-organism conferences that promote even more specialization as individuals embrace even narrower subthemes.

The American Society for Microbiology has responded to microbe-based specialization among its membership by publishing journals, such as the *Journal of Bacteriology*, the *Journal of Virology*, and *Eukaryotic Cell*, with scopes that are delineated by phylogenetic boundaries. Other publishers offer microbe-specific journals, such as *Tuberculosis* and *AIDS*. Highly specialized journals that serve specific fields often have lower impact factors than more-general journals and attract smaller readerships. In response, we observe the paradoxical behavior that specialized scientists prefer to publish their work in more-general journals with higher impact factors. Societies focused on microbiology also struggle with the microbial archipelago. The membership of the ASM is organized among divisions, many of which are similarly delineated by phylogenetic boundaries, resulting in a proliferation of divisions as fields grow and become further subspecialized. The ASM is in the process of reevaluating its structure altogether, aiming toward a more integrative, cross-disciplinary structure that deemphasizes divisions (16). This reorganization was catalyzed by the realization that microbiology is a transcendent discipline, and a divisional structure that partitions knowledge and interactions represents a loss of opportunity.

TRANSDISCIPLINARY RESEARCH AND TEAM SCIENCE

Two landmark scientific discoveries that transformed microbiology in the past century were the development of antibiotics and the discovery that heredity is conferred by DNA. Both were made possible by transdisciplinary research. Although the bacteriologist Alexander Fleming made his famous seminal observation in 1928, more than a decade elapsed before the chemists Ernest Chain and Edward Abraham, working with the immunologist Howard Florey, were able to purify sufficient quantities of penicillin to demonstrate its antimicrobial activity in mice. Further refinements by the biochemist Norman Heatley played a crucial role in making the industrial production of penicillin a reality, just in time for victims of the 1942 Cocoanut Grove nightclub fire to receive this lifesaving treatment (17). In other words, the bench-to-bedside translation of Fleming's observation required contributions from multiple scientific disciplines. Elucidating the structure of DNA and recognizing its potential to encode genetic information similarly emerged from multiple lines of inquiry, including crucial contributions by microbiologists (Oswald Avery, Maclyn McCarty, and Colin MacLeod), physicists (Maurice Wilkins, Francis Crick, and Rosalind Franklin), a biochemist (Erwin Chargaff), and a molecular biologist (James Watson). Another example of fertilization across fields was provided by the enormously influential "phage group" organized by Max Delbrück, a theoretical physicist who teamed up with the molecular biologist Salvador Luria and the bacterial geneticist Alfred Hershey to promote the use of bacteriophages in exploring fundamental biological questions. Today's revolution linking the microbiome to many aspects of human health is only beginning, but it is already clear that multiple fields, including microbiology, immunology, metagenomics, physiology, and bioinformatics, will be playing a major role. Despite its youth, microbiome-related research is itself already becoming highly specialized. Subgroups which focus on health, disease, specific anatomical regions, host species, computational tools, bacteria, fungi, etc., are emerging.

It is therefore not surprising to see an emerging consensus that transdisciplinary research and team science integrating the biological and physical sciences with engineering will be critically important for the future of science (18, 19). The American Academy of Arts and Sciences has proposed numerous recommendations for achieving synergy across disciplines (20). However, it is also evident that the implementation of this vision will need to overcome significant barriers, including the physical segregation of scientists working in different disciplines, the current reward system of science, and the increasingly anachronistic organizational structure of academic institutions (21, 22), as well as deeply rooted epistemic differences between fields (23).

STRATEGIES TO AMELIORATE THE CONSEQUENCES OF SCIENTIFIC SPECIALIZATION

Specialization in science is a necessity due to the enormity of scientific information, and specialization clearly confers significant advantages to the scientific community. However, although specialization is and will remain a fact of life, the disadvantages of extreme specialization might be mitigated. We suggest some strategies to that effect.

Broaden postgraduate training. Postgraduate training today is designed to deliver young scientists into narrow fields of study, such as microbiology, immunology, or cell biology. It is noteworthy that Ph.D.'s are doctorates in philosophy despite the fact that most graduates today have no training in philosophy. Current doctoral programs are designed to teach students more and more about less and less. We have previously argued that current Ph.D. training programs are too narrowly defined and suggested that the first-year curriculum incorporate the fields of philosophical knowledge that bear directly on the scientific method (e.g., ethics, logic, epistemology, and metaphysics) together with increased training in quantitative skills, such as probability and statistics (13, 24). Greater facility with philosophical concepts may facilitate transdisciplinary thinking by broadening the young scientist's intellectual tool kit, and enhanced quantitative skills will facilitate synergy with the physical sciences and improve experimental design. More-broadly trained scientists have a better chance of appreciating other fields and benefiting from their knowledge while retaining the possibility for further specialization later in their training and careers.

Offer cross-field fellowships and transdisciplinary research awards. Scientists who want to switch fields or diversify encounter many obstacles, as discussed above. However, scientists need not become terminally differentiated. One mechanism for barriers confining scientists to their specialized fields would be to design fellowships and awards to be used specifically for cross-field training. Although such fellowships and awards already exist, they are relatively rare, narrowly focused, and designed primarily to recruit investigators to certain fields rather than provide scientists with freedom of movement. For example, the Burroughs Wellcome Fund has an interface award to recruit young scientists trained in the physical sciences and mathematics to biology (http://www.bwfund.org) and several NIH institutes offer training awards to encourage work in specific fields (http://grants.nih.gov/training/careerdevelopmentawards.htm). Many universities continue to permit a sabbatical leave as a mechanism for established scientists to visit other laboratories and become familiar with new fields of study. However, sabbaticals are increasingly difficult to obtain, as scientists are burdened with the immense efforts needed to keep their laboratories operational at times of scarce funding and to meet administrative responsibilities. An increase in dedicated career development awards with the goal of diversifying scientists' expertise may have a salutary effect on the increasing specialization of science.

Provide plain-language summaries of journal articles. One seemingly inevitable consequence of the specialization of science is that fields develop increasingly arcane nomenclature. This, in turn, reduces interdisciplinary communication, promotes further specialization, and increases the isolation of fields. One mechanism to encourage communication would be to require plain-language summaries of scientific papers, and several journals are already using this approach. For example, *mBio* requires a plain-language summary articulating the importance of the work (25).

Create new opportunities for transdisciplinary interactions. Greater efforts could be made to bring together researchers with complementary expertise through transdisciplinary work-in-progress meetings and centers, such as the ASM General Meeting and FASEB Science Research Conferences, which actively encourage exchanges between fields. We acknowledge that the tribal organization of microbiology and immunology is unlikely to change in the foreseeable future, but there are encouraging efforts to forge transdisciplinary links. Specialized meetings are likely to remain very popular. Nevertheless, it is possible for fields to benefit from advances in other fields and to reduce the problems associated with groupthink. Mechanisms to reduce isolation can include inviting speakers from other fields to specialized meetings, encouraging cross-field visitations, and actively supporting interface research. However, the success of initiatives is critically dependent on efforts by the participants to reach out to other groups. For example, inviting speakers from other groups to specialized meetings will succeed only if each speaker makes an effort to integrate his theme with that of the audience, which usually requires the creation of a new type of presentation.

Administrative changes that promote transdisciplinary interactions. Seminars, journal clubs, and scientific meetings are often structured around individual departments or fields. Physical isolation of scientists is an important contributor to the development of intellectual silos within institutions. One mechanism for promoting transdisciplinary research is the creation of institutes within institutions that include individuals from diverse fields and provide opportunities for interactions outside specialized fields. The development of institutional criteria to recognize the contribution of individuals to team science projects when there are appointment and promotion assessments should also be encouraged.

Adam Smith rightly foresaw the benefits of specialization in complex human endeavors. However, specialism carries a price, and a healthy enterprise, whether a factory, a laboratory, or a global community, requires both specialist expertise and generalist thinking. The chemist Leo Baekeland, whose invention of Bakelite ushered in the era of plastics, expressed the following concern about the specialization of science more than a century ago (26):

> If specialization may be advantageous for increasing our productiveness in a given field of activity, over-specialization, on the other hand, may develop one-sidedness; it may stunt our growth as men and citizens; even for persons engaged in scientific pursuits it may render impossible the attainment of true and general philosophic conceptions.

Efforts to remove barriers to interaction between scientific disciplines are likely to yield substantial benefits in the future.

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