CHAPTER 8

Biological sciences

WARREN BURGGREN, KENT CHAPMAN, BRADLEY KELLER, MICHAEL MONTICINO, AND JOHN TORDAY

Curiosity, an innate human characteristic, is inevitably directed to the biological world of which we are an integral part. Indeed, curiosity about our biological surroundings and its role in it pre-dates the written word, as evident in ancient cave drawings at Lascaux (*c.* 16,000 BP) depicting the living world around the artist. Likely as ancient is the interplay between biology (as our ancestors perceived it) and other human endeavors, including religion, art, and the emergence of technology.

From these origins has arisen the discipline of biological sciences—a discipline that is fundamentally shaped by its interdisciplinary activities. Moreover, interdisciplinarity in the biological sciences is constantly shifting as new technologies and theories arise, evolve, and mature and—sometimes—fade away. Thus, the biological sciences, like many scientific disciplines, are constantly subjected to an 'the interdisciplinary cycle' shown schematically in Fig. 8.1. The merger of biology and chemistry, forming the new discipline of biochemistry (discussed below), is a classic example. Emerging as a new discipline (steps 4 and 5 in Fig. 8.1), biochemistry is now a long-standing discipline that is itself going through another turn of the interdisciplinary cycle through its interactions with information science and nanotechnology.

Against this dynamic backdrop of constantly changing associations with other disciplines, we first offer a series of vignettes or case studies on how interdisciplinary studies between the biological sciences and other science and engineering fields have yielded a wealth of new insights and practical products. We then discuss the advantages and challenges of undertaking interdisciplinary activity in the biological sciences. Befitting the task, as well as reflecting the collaboration typical of the biological sciences, the 'we' represents a collaboration of authors with backgrounds in physiology, biochemistry, medicine, and mathematics who collectively have experienced and benefited from team approaches to problem solving.

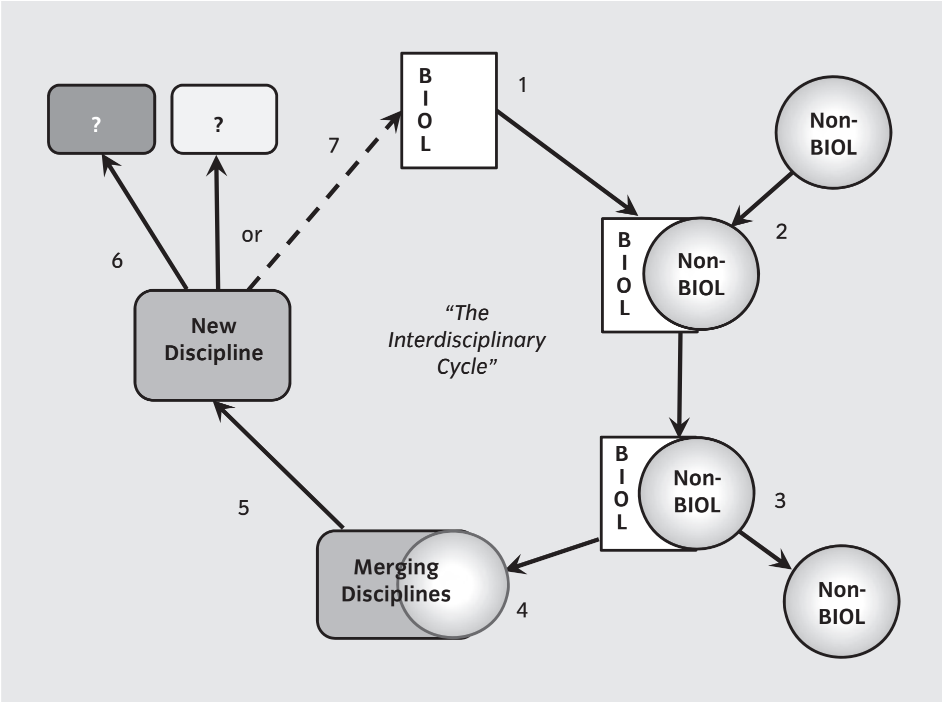

Figure 8.1 The interdisciplinarity cycle, in the biological sciences and other disciplines experiencing interdisciplinarity cross-fertilization. (1) A free-standing discipline such as biology regularly experiences the influence of non-biological disciplines. (2) This co-mingling of ideas and techniques can ultimately be only fleeting (3), or it can result in a true merger of the disciplines (4). This new discipline, formed from the merger of biology and non-biology (5), may eventually fragment into new disciplines (6), or can persist (7) to enter the interdisciplinarity cycle once again.

8.1 Case studies in biological interdisciplinarity

The interdisciplinary reach of the biological sciences is extensive—indeed, too far-reaching to cover completely in this chapter. As an alternative approach that is hopefully illustrative, we present several case studies of how the biological sciences have effectively interfaced with engineering, medicine, mathematics, and chemistry.

8.1.1 Biology and medicine

Biology and medicine—two distinct disciplines each with their own approaches, currencies, and outcomes—have nonetheless coexisted as intertwined disciplines for more than two millennia. The study of animals has been used to understand principles in medical science since Aristotle (384–322 BCE) and Erasistratus (304–258 BCE), who were among the first to experiment with living animals. Aelius Galen (129–200 CE), a second-century Roman clinician, dissected pigs and goats. In the seventeenth century, William Harvey (1578–1657) described the circulation of blood in mammals. In the eighteenth century, Stephen Hales (1677–1761) measured blood pressure in the horse and Antoine Lavoisier (1743–94) placed a guinea pig in a calorimeter to prove that respiration was a form of combustion. Claude Bernard (1813–78) established animal experimentation as part of the standard scientific method. In the 1870s, Louis Pasteur (1822–85) demonstrated the germ theory of medicine by giving anthrax to sheep.

It should be noted that up to that point in human thought, Western society embraced the belief in a Great Chain of Being, ordering all of existence is a continuous natural hierarchy that placed humans between God and all other animals. It was Charles Darwin (1809–82) who destroyed the belief in purpose in nature with the publication of *The origin of species* in 1859. By the turn of the twentieth century Ivan Pavlov (1849–1936) used dogs to describe classical conditioning, and Sir William Osler (1849–1919) developed the field of pathophysiology, creating a systematic way of understanding disease and health and their relationship to the biological sciences.

The descriptive approaches alluded to here dominated biology and medicine until the advent of transgenic animals, and the publication of the human genome and those of other model organisms (mouse, chicken, fruit fly). Recent discoveries that patterning genes are common to all of animal life from flies to humans, and that humans have fewer genes than a carrot (25,000 versus 40,000), have emphasized the importance of comparative studies at the cell/molecular level for understanding both biology and medicine. As a result, modern biology is now expected, by analogy to physics, to generate a periodic table, formulate its own equivalent to $E = mc^2$, and develop a quantum mechanics of a predictive biology that relies less on time-honored empirical observation and much more heavily on prediction (Torday 2004).

Unfortunately, such advances cannot be achieved by a direct analysis of available data from species, because organisms have evolved through an emergent and contingent process in which new species have appeared while others have become extinct. But the fossil record of evolution is embedded in the developmental processes involved in the formation of existing organisms, and can be elicited by determining the genetic basis of phenotypes across species as they develop, i.e. ontogeny recapitulates phylogeny. Based on this knowledge, the indirect methods of developmental and comparative biology, reduced to cells and molecules, have been used to connect the dots between first principles of physiology (e.g. homeostasis, acclimation) and the scientific basis for a more prediction-based medicine in the future (Torday and Rehan 2009a).

For centuries biology has used disease to leverage our knowledge and understanding of health, and vice versa, since all biologists had available were descriptive phenotypes (the outward appearance of an organism, as opposed to its genotype, its genetic makeup). However, with the merger of genetics, molecular biology, and physiology into the subdiscipline of genomics (the study of genes and their functions), we can now address the questions of health and disease as a continuum, based on genetic mechanisms as they apply to the relevant phenotypes. Furthermore, the discovery of so-called 'patterning genes' has led to the recognition of fundamental commonalities between very different appearing phyla (e.g. fruit flies and mice, nematode worms and humans). Along with the sequencing of the genomes of fishes, amphibians, and birds, it is now possible to exploit evolutionary–developmental biology to provide a Rosetta Stone for helping to decipher the organic nature of disease, rather than describing health as the absence of disease. These advances have primarily arisen through the interdisciplinary commingling of basic life sciences and advanced medicine.

Evolutionary biology is fundamental to the biological sciences. Plugging genes and related phenotypes of interest into an evolutionarily robust model of animal development will allow us to decipher causes of human diseases. Using this approach will allow biologists to see the continuum from adaptation to maladaptation and ultimately to disease. Such a perspective would finally offer a scientific basis for monitoring health independently of disease, ushering in a new era of preventive medicine (Torday and Rehan 2009a). The key to such an approach is to identify the developmental cellular and molecular mechanisms that are fundamental to an organism's structure and function. Such studies are conventionally conducted by developmental biologists. Unfortunately, they only rarely involve biologists familiar with comparative, phylogenetic analyses across species. As a result, collaboration primarily occurs through the passive capture of data in the biological and medical literature that examines the development of phenotypes at the cell/molecular level. A number of national and international meetings have fostered more activist approaches involving developmental biologists and medical researchers, and a website (<http://evolutionarymedicine.labiomed.org/>) has been established to draw attention to this unconventional, but biologically sound and effective, interdisciplinary approach.

It has previously been suggested that life scientists should generate the biologic equivalent of the periodic table. Drilling down to the molecular pathways that have given rise to complex physiologic traits is the key to understanding the first principles of physiology as the scientific basis for predictive medicine (Torday and Rehan 2009a). For example, by identifying the genes that mediate the 'cross-talk' between the cells of the mammalian lung, gene regulatory networks responsible for lung evolution have been traced back to the swim bladder of fishes, genetically linking mechanisms for buoyancy, gas exchange, and nutrition at the cell–molecular level (Torday and Rehan 2009b). By systematically reducing complex traits to their genetic phenotypes developmentally across species, and by then sharing this vast number of data via public databases, biologists will ultimately be able to unravel complex physiologic principles relevant to both biology and medicine. There are, of course, dangers in unmitigated reductionism, such as the failure to identify emergent properties that result from the interactions across components and levels. However, the success of a reductionist approach as one of many concurrent approaches shows great promise in medical advances.

The discipline of biology is on the verge of a sea change in the interactions between biology and medicine, if only it can utilize the huge data sets being created (via exploiting yet another interdisciplinary field—bioinformatics). By abandoning the old paradigm of descriptive biology, and moving into a mechanistic paradigm based on evolutionary principles, it may be possible to progress towards an era of predictive biologic science. This will enable biologists to address counterintuitive aspects of biology such as why the lens of the eye is composed of digestive enzymes, or why the lung is a hormone-secreting endocrine organ. With the anticipated interdisciplinary activities between predictive biology and predictive medicine (Torday and Rehan 2009a) society's burden of chronic diseases may be significantly diminished.

8.1.2 Biology and chemistry

One of the oldest and most productive interdisciplinary amalgamations within the life sciences is that of biology and chemistry into 'biochemistry'. Biochemistry involves many different areas of research, but at its heart it is the study of the organic molecules (those containing carbon) and their chemical reactions within living systems. Biochemists today may not readily imagine themselves as interdisciplinary, yet their work bridges both the life and physical sciences.

That biochemistry is now less frequently thought of as at the interface of two disciplines is due in large part to its maturation as a discipline in its own right over the last 150 years. Generations of scientists are now trained with a common view of their science and are comfortable using the languages of either biology or chemistry. In fact by the mid twentieth century, entire departments of biochemistry were commonplace among many colleges and universities, where none had existed 50 years earlier.

The early history of biochemistry developed from the general concept that living materials catalyze chemical reactions. Probably most exemplary are the studies of the fermentation process by yeast. Most of the early research was carried out in the late 1800s and early 1900s by scientists trained as chemists. Indeed, Eduard Buchner received the Nobel Prize in Chemistry in 1907 for his pioneering discoveries of the biochemical fermentation of sugar by cell-free systems, a clear recognition of the emerging science of 'biological chemistry'.

The popularity and power of biochemical approaches led to widespread exploration of biological systems where chemists, familiar with the properties and analysis of organic molecules, sought to work with biologists experienced in physiology. The products of these interactions have created a remarkable knowledge base over the last 100 years, and have spawned new interdisciplinary lines of research. In this short space it is not possible to provide a complete list of the many scientific contributions that can be attributed to the field of biochemistry. However, the quest to understand the mechanisms that drive biological systems has been the major driver for the emergence and maturation of biochemistry. Indeed, numerous major discoveries have been made possible through the interdisciplinary research of biochemistry, including the identification of:

- the structural features of major classes of macromolecules such as DNA (which contains the gene sequence of an animal, RNA (involved in the replication of DNA) and proteins,
- the basis of enzymes, which facilitate metabolic reactions,
- the mechanisms of photosynthesis, for the biological conversion of light to chemical energy and reduction of inorganic carbon,
- the machinery of cellular respiration and membrane transport, for biological energy conversion and nutrient and waste movement in and out of the cell,
- the genetic code, whereby variations in the sequence of just four nucleotide bases universally explains the nature of proteins from bacteria to human,
- the basis for protein synthesis and turnover, for the production, regulation, and recycling of cellular machinery,
- the enzymes that regulate gene expression.

Since 1901, at least 35 Nobel Prizes in Chemistry and many more in Physiology and Medicine (<http://almaz.com/nobel/>) have been awarded for discoveries in biological chemistry, illustrating the tremendous rewards of working at the interface of chemistry and biology. Many of these discoveries have led to entirely new fields of interdisciplinary research. For example, out of the structural determinations of DNA, RNA, and proteins has developed the new discipline of structural biology; out of the enzymology of transcription and the genetic code has arisen the discipline of molecular biology. These two newer disciplines, much like the newly emerging area of systems biology, have been driven by the scope of biological questions, but have depended upon the contributions of scientists from many disciplines—including mathematics, computer science, chemistry, biology, and physics.

Interdisciplinary collaborations in the life sciences—or any other area, for that matter—are most successful when the overall outcome is greater than the sum of its parts, and when all collaborators have a vested commitment in and benefit from that outcome. An excellent example of this in biochemistry is in the recent area of comparative metabolomics—essentially the simultaneous profiling and quantification of all metabolites from a tissue or cell type. This has analytical biochemistry at its basis, but on a high-throughput, massive scale (many thousands of chemical components). These types of experiments have required the development of sophisticated mass spectrometry-based instrumentation, the know-how for sample preparation, expertise in separation technologies and robotics, computational capabilities for data analysis, and someone to know the relevant questions to address. Success depends upon contributions from chemistry, biology, computer science, mathematics, and instrument design and engineering, and it could not be achieved without any one of these components.

Biochemistry continues to evolve as an interdisciplinary activity. This is evident now with the era of 'omics'. In the 1970s and 1980s, a combination of biochemical and molecular genetic approaches toward biological questions resulted in an interdisciplinary area of research referred to as 'biochemical genetics'. This term has fallen out of favor, but the emphasis on understanding the biochemical functions of genes remains at the forefront of life sciences today. The areas of genomics, proteomics, metabolomics, etc. are an extension of the concept of understanding gene function, but on a genome- or system-wide scale. With the rapidly advancing tools for analyzing DNA sequences, monitoring gene expression, identifying proteins, and quantifying metabolites, information is being gathered on an enormous scale.

Instead of an individual research laboratory experimentally addressing the function of a single gene over many years, teams of scientists are attempting to understand biology from an entire 'systems-wide' approach. This requires expanded capabilities orders of magnitude greater than those of two decades ago when the first gene sequences were being collated in a database called GenBank. For example, as of February 2008, there were over 190 billion bases of nucleotide sequence information archived in the GenBank databases (<http://www.ncbi.nlm.nih.gov/Genbank/index.html>). To accommodate these increasing numbers of gene sequence, gene expression, protein structure, and metabolic data, requires new computing power, expertise in predictive programs, powerful statistical methods, and computational algorithms. Questions can now turn to the functions of thousands of genes, proteins, and metabolites at once, helping to address everything from human health to agricultural production. These grand challenges require the collaboration of scientists with expertise in many disciplines in addition to biochemistry, and will involve tools and languages yet to be developed; but it is certain that interdisciplinary activity across traditional boundaries of science and engineering is the way forward.

8.1.3 Biology and engineering

The relationship between biology and engineering is an old one. For example, Leonardo da Vinci (1452–1519) was a prototypic artist/inventor/anatomist/engineer. His studies on human form and function revealed the interdependence between biological processes and biomechanical function and physical forces. However, da Vinci's efforts extended beyond the reduction of complex processes to include the design and fabrication of structures as representations of what he observed in nature. Additionally, da Vinci showed us the great potential in the marriage of biology and mechanical functions. Indeed, modern engineering disciplines now encompass a broad matrix of biological topics, including developmental biology, bioenergetics, biomechanics, biomaterials, artificial intelligence, and bionics related to the development of artificial organs.

Yet the marriage between biology and engineering is neither easy nor automatic. Consider the comments of Fung and Tong (2001) in their classic engineering text, *Classical and computational solid mechanics*:

> Engineering is quite different from science. Scientists try to understand nature. Engineers try to make things that do not exist in nature. Engineers stress invention. . . . Most often, (engineers) are limited by insufficient scientific knowledge. Thus they study mathematics, physics, chemistry, biology and mechanics.

Unfortunately, the inverse is not true—biologists, who also are often limited by insufficient knowledge, are not (yet) drawn in great numbers to study engineering. Yet, many biological processes occur within biophysical environments that are dynamic and rapidly changing. Analytic engineering principles and paradigms have been developed and applied to investigate and quantify many of these dynamic interrelationships, and emerging biology–engineering interdisciplinary partnerships are now poised to take advantage of them. Here we consider a few representative vignettes that highlight the unique opportunities and insights that have gained through the interface of biology and engineering.

Our current understanding of the developmental biology of the heart and blood vessels has been substantially influenced by interdisciplinary interactions between biologists and engineers. One of the most fundamental processes during animal development is the growth and remodeling of the embryonic heart from a single cell, to a peristaltic tube and finally into a multichambered organ with functioning unidirectional valves, a specialized conduction system for electrical impulses, and optimized blood flow to correctly direct deoxygenated and oxygenated blood to the tissues. Complex processes of heart tissue formation, including how heart cells, tissues, and structures (chambers, valves) grow and change, initially quantified by developmental biologists and physiologists, have now been analyzed by bioengineers. Using computer technology, cardiovascular physiologists working with bioengineers can now actually visualize previously only imagined forces in the wall of the beating embryonic heart. This interdisciplinary partnership has provided new understanding of how sheer and strain in the heart walls actually help shape the heart and its growth. In fact, the interdisciplinary interactions of developmental biology and engineering used so effectively in cardiovascular biology have now been expanded to provide relevant insights and identify novel questions across an extremely broad landscape of developmental and comparative biology, ranging from protein configurations to whole embryo structure (Davidson *et al.* 2009).

Regenerative medicine (the creation of replacement tissues and organs) is another example of the emerging products of interdisciplinary collaborations between biologists, physicians, and engineers. By exploring developmental processes in tissue and organ generation, bioengineers have developed new technologies being applied to the design and fabrication of biomaterials (materials that can become part of or even replace original tissues). Bioengineering approaches have also led to a large potential commercial market for biotherapeutics (therapeutic substances produced by biological means, e.g. vaccines).

Such insights have led to the rapid expansion of regenerative medicine. In fact, tissues and organs generated *in vitro* ('in the test tube') have approached the critical phase of initial clinical trials. Bioengineering regeneration techniques have also been employed to investigate the biomechanics and regulation of cardiac valve formation, with the goal of generating robust replacement heart valves *in vitro* (Engelmayr *et al.* 2008). At the cellular and molecular levels, biologists and engineers are contemplating the creation of nanomachines that are injected into the bloodstream of a patient, travel to their targeted tissues, and then carry out a specific suite of activities which can include actually permanent assimilation into the tissue. Of course, ethical issues arise from regenerative medicine (see Callahan,Chapter 29 this volume), with an uncontrolled extrapolation leading to the specter of 'borg-like' creatures where the boundary between human and machine is blurred.

Successful collaborations between biologists and engineers, such as the examples of heart development and organ regeneration outlined above, are being catalyzed by a targeted expansion of funding in the United States by the National Institutes of Health, the National Science Foundation, and numerous foundations that support interdisciplinary teams. But even as collaborations that lead to advances in health are expanding, there is also a great deal of attention being paid to potential military applications resulting from interdisciplinary activities between biologists and engineers. As just one example, the exoskeleton of invertebrates such as insects and crabs is being studied with a view of providing an external 'exoskeleton' for soldiers. This external, motor-driven scaffolding would allow them not only to carry more gear, but potentially even to be remotely activated to march wounded soldiers out of danger.

The interdisciplinary collaborations between engineers and biologists often revolve around mathematical analyses. We now turn to the highly productive collaborations between biologist and mathematicians.

8.1.4 Biology and mathematics

Biology, as a quantitative science, has always depended heavily on mathematics. Collaborations between biologists and mathematicians, as a focused area of research, began in the early twentieth century with the study of disease transmission (epidemic models), population dynamics, and genetic frequency models. Building upon this foundation, the past few decades have seen tremendous growth in the advances made through mathematical methods in almost every area of biological research, especially with respect to modeling biological processes. Agent- or individual-based models, supported by increased computational capabilities, have joined classic mathematical models to enhance understanding of population dynamics, including processes of disease transmission.

Early mathematical population models have also provided the groundwork for significant advances in cellular systems modeling, with direct applications to oncology as biological knowledge of cellular responses and computational methods have enabled more realistic models for the treatment of cancer. Mathematical models of the genetics of organisms and their resulting features continue to develop, finding new applications in epidemiology. This, in turn, has motivated meta-analysis of databases of genetic sequences of different animals (and plants), which has resulted in ideas for new disease therapies. At the same time, examination of the molecular basis of the formation of new species has deepened our understanding of evolutionary relationships. Recent advances in the theory of complex systems are providing new insights into physiological systems with multiple feedbacks and interacting components (Burggren and Monticino 2005). Indeed, the list of biomathematical applications is ever-expanding, including the analysis of complex images (e.g. the three-dimensional images of cells provided by confocal microscopes), and the interpretation of the complex folding of proteins, of data from new genetic techniques (e.g. microarrays), and of complex nerve networks in the brain.

The rich diversity of progress described above, and the promise of future advances, has led to the establishment of strong interdisciplinary programs in biomathematics and bioinformatics at a wide variety of institutions. Graduates from these programs hired into traditional mathematics and biology departments at universities are influencing departmental culture (including promotion and tenure criteria; see Phirman and Martin, Chapter 27 this volume). While significant challenges remain, there is a growing realization among mathematicians that not being involved in interdisciplinary work with biologists means missing out on some of the most exciting discoveries of our time.

Biologists and mathematicians cannot just decide to work together, and then do so. Mathematicians entering into collaboration with biologists often require a crash course in the basic biology underlying the research, and must relearn (or learn for the first time) what most undergraduate biology majors know. It also requires patience from one's biology colleagues who take for granted a certain knowledge base when interacting with colleagues. The biologists will appreciate the same patience about topics a mathematician may assume that every educated person knows—when the reality is that very few people know (or care) about 'Kolmogorov–Sinai entropy' or 'isomorphism groups'.

Even simple vocabulary can be an early stumbling block in collaboration between biologists and mathematicians. Not only may terms mean different things in different disciplines, but there are different levels of precision in how terms are used. Confusion can especially arise with words that have both common English and technical definitions. For example, the term *chaotic* is a commonly used term that nonetheless has a precise and much narrowed mathematical meaning. A biologist may be perfectly comfortable characterizing a system as chaotic based on perceived disorder; while a mathematician would argue that the system does not meet the definitional requirements, and merely has a complicated response function. It is important to calibrate vocabulary early in a collaboration to reveal common core ideas and avoid misunderstandings.

Much discussion in this chapter has focused on why and how biologists engage in interdisciplinary work with non-biologists. A complementary question is, why would non-biologists—in particular, mathematicians—collaborate on problems with biologists? A compelling reason is intellectual curiosity. It is refreshing to venture out of increasingly narrow disciplinary subfields to gain a substantive understanding of research questions in other fields. Collaboration can also provide a rewarding opportunity to make significant contributions to problems that have importance outside of mathematics, especially to bioscience questions that have clear applicability. Consider that the very top mathematics journals typically have a so-called 'impact factor' (a calculation of overall impact based on the frequency with which its articles are cited) of less than 3, while some biological journals have impact factors over 20. This is not a judgment on the relative intrinsic worth of disciplines. It does, however, suggest a certain insularity of pure mathematics research and the prospect for extending reach that collaborations with biologists afford.

Effective collaboration also requires flexibility. It is often not clear going into an interdisciplinary project which mathematical tools will be needed to best address the problem. So, broad mathematical awareness is extremely valuable, as well as the willingness to learn and apply mathematics outside of one's immediate area of expertise. Interdisciplinary work thus provides mathematicians opportunities to learn new areas of science as well as occasions to apply a variety of mathematical techniques.

Of course, these very same arguments apply to biologists attempting to work with mathematicians, and each has much to offer to their colleagues across the disciplinary boundaries. Mathematicians bring not only a toolbox of modeling and analysis techniques to biological projects, but also a useful level of rigor and clarity of analytical thought. The challenge is to engage more biologists and mathematicians in interdisciplinary studies that make significant contributions to the increasingly quantitative field of biology. This can be partially achieved by training a new generation of mathematicians within undergraduate and graduate programs that have substantive interdisciplinary components. However, it is also important to encourage traditional, established mathematics programs to participate. This is an incredible time, filled with opportunities, for mathematicians to apply their distinctive training and expertise in fields outside their discipline.

8.1.5 Biology and beyond

The case studies described above show the fruits of the mergers of the biological sciences with the major disciplines of medicine, chemistry, engineering, and mathematics. But many other established interdisciplinary bioscience-based fields exist, including biogeography (Lomolino *et al.* 2006), bioinformatics (Lesk 2008), biophysics (Nölting 2003), biostatistics, (Glantz 2005), and biotechnology (Pisano 2006). Particularly exciting developments are occurring in the interdisciplinary merger of biology and nanotechnology. For example, materials scientists intent on manufacturing machines at the molecular level are using the effective molecular recognition properties of DNA to allow this molecule to act as a template, generating novel materials with useful properties at highly controllable rates (Priyadarshy and Shankar, in press).

Of course, the reach of biology extends well beyond the sciences and technology into interdisciplinary interactions within the social sciences, arts, and humanities. Space does not allow us to expand into this rich area of discussion, but a few examples can suffice as an introduction.

Environmental issues have become a very active area of collaboration between humanists and biologists. Environmental problems typically involve an intricate mix of bio- or environmental science, environmental philosophy, and policy concerns (see Callicott, Chapter 33 this volume). Bioethics, a related field founded in the 1960s, addresses ethical and philosophical questions that arise from advances at the intersection of biology and medicine (see Callahan, Chapter 29 this volume). Political science, government, and history are interwoven with biological principles. For example, studies of peace and war are often interpreted in the context of sociobiology, and evolutionary theory has been turned towards an understanding of human conflict (e.g. Vergata 1995). Indeed, human behaviors for good or ill, are often placed within a biological context, most notably using E. O. Wilson's (1975) concept of sociobiology. As computing and robotic technologies continue to evolve, the field of human–computer interactions will have relevance to social behavior as well as to the investigative sciences.

Biology has, of course, long been a topic for the arts (consider Claude Monet's *Water lily pond* or Van Gogh's *Sunflowers*). However, biology has also depended on art in the form of medical illustration. This dependence has existed for millennia, with medical illustration likely originating in Hellenic Alexandria during the fourth century BCE, and evident as mature interdisciplinary activity in the work of such famous illustrators as Leonardo da Vinci and Andreas Vesalius (1514–64).

Biology and religion have a long and sometimes uneasy history of coexistence, most notably in recent years in debates over evolution, creationism, and intelligent design. More fruitfully, perhaps, interdisciplinary studies are helping to understand the origins of social morality, cooperation, peace, and war (e.g. Bekoff 2001), as well as the evolution of religion (Dow 2006).

8.2 What are the impediments to interdisciplinarity in the sciences?

Given the richness of interdisciplinary collaborations described above, why don't more mathematicians, biologists, chemists, physicists, and others step across disciplinary lines? There are myriad potential impediments—none insurmountable, but many quite formidable. Since scientists often use jargon, or have specialized knowledge that other team members lack, frequent communication is essential for all to work productively together. Thus, it can be difficult to develop a common working knowledge, or understanding of the complementary discipline's perspective, capabilities, and limitations. Scientists are most comfortable within the confines of their narrow disciplines, but much less so when venturing into unfamiliar territory. Overcoming the obstacle of a common understanding may take many frustrating discussions, much like learning to communicate in another language. Some potential interdisciplinarians lack the patience for this process.

Interdisciplinary collaborations also take time to bear results. The tenure clock doesn't recognize the extra time it takes to absorb the key concepts in the secondary discipline, to develop a shared view of a problem, and then search for appropriate techniques. Consequently, it is not unusual for junior faculty to be advised by their mentors not to pursue interdisciplinary work until after tenure. All too often, however, by the time tenure has been achieved, research paths have developed into deep ruts for which there are few institutional incentives to climb out of (see Phirman and Martin, Chapter 27 this volume).

It is also difficult for many academic (and non-academic) evaluators to judge the value of interdisciplinary projects. Consider, for example, the challenges to mathematicians proposing to work with biologists. Mathematics departments, like all academic departments, evaluate the research productivity of their faculty by the number of articles published in disciplinary journals and the quality of the journals in which articles are placed. Mathematics journals follow an exacting theorem–proof format. A collaboration with biologists will typically not produce a fundamental advance in mathematics (of course, sometimes this does happen, enriching both mathematics and biology). Even if it does, the theorem–proof exploration of the result would rarely find its way into a biology journal article. Traditional mathematics departments are challenged to evaluate the worth of an article that does not contain a proof, no matter how innovative or useful the application. Often, faculty members are admonished to translate the application into work that can stand on its own in a conventional mathematics journal. Thereby, the work necessary to attain evaluations similar to those of departmental colleagues not collaborating outside their discipline is at least doubled.

Even when scholarly work can be easily evaluated with regard to content, there may be an attached stigma (or at least lack of appreciation) for the venues in which interdisciplinary work appears. Front-line, cutting-edge interdisciplinary journals that are the 'must-publish' targets for interdisciplinarians may nonetheless have low impact factors and very small circulations of a few thousand compared with the disciplinary 'usual suspects' such as *Science* (with a very high impact factor and a paid circulation of more than a million). Put differently, scientists and mathematicians working in interdisciplinary areas still face the significant challenge that a paper in *Science* is typically regarded as far, far more significant than a paper in, for example, the interdisciplinary journal *Science Studies*, targeting not only scientists but sociologists, philosopher, historians, and psychologists.

Although there are many impediments to interdisciplinarity, there are many ways to actively promote such approaches. Interdisciplinary scientists need to remain open to new ideas, commit to learning alternative approaches and, perhaps above all else, be patient with respect to their own advancement, that of their colleagues, and ultimately of the project. Beyond the individuals, institutional practices need to be implemented that provide clear incentives to departments and faculty to engage in interdisciplinary research projects. This can start proactively with, for example, workshops and other educational opportunities for evaluators so that they can learn of both the promise and pitfalls of interdisciplinary research.

8.3 Conclusion

The case studies described above demonstrate the power of interdisciplinary approaches in the biological sciences, drawing upon a variety of disciplines in the sciences and beyond, for generating new perspectives, approaches, hypotheses and ideas for future experiments. Also apparent is that interdisciplinarity in the biological sciences is typically not just a single person working in an interdisciplinary area, but rather 'sympathetic' disciplinarians working together to bring the best of their training and knowledge together in new and innovative ways. Environments such as think tanks, centers, and institutes have all proven to be highly useful for getting dissimilar types of people together to work on interdisciplinary issues in biological sciences.

Yet, interdisciplinary work in the biological sciences can be challenging. Communicating with collaborators in other disciplines requires (re)learning disciplinary-dependent concepts, adopting new vocabulary, and committing to new approaches. Even when successfully completed, interdisciplinary science may not be fully appreciated by conservative or more traditionally inclined evaluators.

Yet interdisciplinarity in the biological sciences is burgeoning, driven by a spectrum of motivations ranging from unbridled intellectual curiosity to demonstrated practical solutions to engineering and medical problems. Clearly, in the future the biological sciences will continue to operate within an interdisciplinary cycle (Fig. 8.1), spawning new subdisciplines and, in time, changing the fabric of biology itself. As stated by Thomas Kuhn (1962), we won't recognize the most fundamental paradigm shifts in science until after they have occurred.

References

Bekoff, M. (2001). Science, religion, cooperation, and social morality. *BioScience* **51**(3), 171.

Burggren, W.W. and Monticino, M.G. (2005). Assessing physiological complexity. *Journal of Experimental Biology* **208**, 3221–32.

Davidson, L., von Dassow, M., and Zhou, J. (2009). Multi-scale mechanics from molecules to morphogenesis. *International Journal of Biochemistry and Cell Biology* **41**(11), 2147–62.

Dow, J.W. (2006). The evolution of religion: three anthropological approaches. *Method and Theory in the Study of Religion* **18**(1), 67–91.

Engelmayr, G.C., Jr, Soletti, L., Vigmostad, S.C. *et al.* (2008). A novel flex-stretch-flow bioreactor for the study of engineered heart valve tissue mechanobiology. *Annals of Biomedical Engineering* **36**, 700–12.

Fung, Y.C. and Tong, T. (2001). *Classical and computational solid mechanics*. Singapore: World Scientific Press.

Glantz, S. (2005). *Primer of biostatistics*. New York: McGraw-Hill Medical.

Kuhn, T.S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lesk, A. (2008). *Introduction to bioinformatics*. New York: Oxford University Press.

Lomolino, M.V., Riddle, B.R., and Brown, J.H. (2006). *Biogeography*, 3rd edn. Sunderland, MA: Sinauer Associates.

Nölting, B. (2003). *Methods in modern biophysics*. New York: Springer.

Pisano, G.P. (2006). *Science business: the promise, the reality and the future of biotech*. Cambridge, MA: Harvard Business School Press.

Priyadarshy, S. and Shankar, L. (in press). *DNA nanotechnology*. Boca Raton, FL: CRC Press.

Torday, J.S. (2004). A periodic table for biology. *The Scientist* **12**, 32–3.

Torday, J.S. and Rehan, V.K. (2004). Deconvoluting lung evolution using functional/comparative genomics. *American Journal of Respiratory Cell and Molecular Biology* **31**, 8–12.

Torday, J.S. and Rehan, V.K. (2009a). Exploiting cellular-developmental evolution as the scientific basis for preventive medicine. *Medical Hypotheses* **72**(5), 596–602.

Torday, J.S. and Rehan, V.K. (2009b). Lung evolution as a cipher for physiology. *Physiological Genomics* **38**, 1–6.

Vergata, A.L. (1995). Darwinism, war and history: the debate over the biology of war from the 'Origin of species' to the First World War. *Medical History* **39**(3), 378–9.

Wilson, E.O. (1975). *Sociobiology: the new synthesis*. Cambridge, MA: Harvard University Press.