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CULTIVATING EMERGING AND BLACK SWAN TECHNOLOGIES

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ABSTRACT

Emerging technologies, defined as contemporary cutting-edge developments in various fields of technology, are generally associated with the potential for large impact on society. In a recent op-ed, “The coming Tech-led Boom” (Wall Street Journal, January 30, 2012), Mills and Ottino list three grand technological transformations - big data, smart manufacturing, and the wireless revolution - poised to transform this century as much as telephony and electricity did in the 20th century. This list is by no means comprehensive and most likely misses technologies that are not yet recognized, but may still carry an extreme impact - i.e., the so-called Black Swans, as defined by New York Times best-selling author, Nassim Nicholas Taleb, in his book, The Black Swan. Taleb cites the example of three recently implemented technologies that most impact our world today - the Internet, the computer, and the laser - and notes that all three were unplanned, unpredicted, and unappreciated upon their discovery, and remained unappreciated well after initial use.

In this paper, we will examine several emerging technologies, present a methodology to create a breeding ground for potential Black Swans, and finally discuss the societal and ethical aspects of these technologies.

Keywords:

INTRODUCTION

Looking back at the beginning of the 20th century, the country was not electrified; radio, TV, computers, telephone and the Internet did not exist; and the average life span was only 46 years. Much of society’s transformation since then has been made possible through the technological breakthroughs powered by science and engineering. One could argue that in the last century mankind has seen more change than at any point in history. However, if the early years of the 21st century are any indicator of the years ahead, we can still expect large unprecedented and fast-paced change, made possible again through a confluence of powerful technologies.

In a landmark NSF/DOC sponsored report, Roco and Bainbridge [1] presented a consensus view among leading experts from government, academia and private sector that four powerful “converging” technologies - nanotechnology, biotechnology, information technology, and cognitive science (NBIC) – are poised to unleash new understanding of matter at the atomic scale and the complex working of the human brain, creating opportunities for new industries, robust job growth, and enhanced human capabilities. Consider, for example, nanotechnology. Perhaps the most enabling of the converging technologies, it is widely expected to usher in the 3rd industrial revolution with a wide spectrum of applications including those in electronics and computers, medicine and health, aeronautics and space applications, environment and energy, biotechnology and agriculture, and materials and manufacturing. Each one of the other NBIC technologies is equally powerful but it is the integration of a subset or all of these that holds the most promise.

Looking over the horizon, we believe that the confluence of NBIC and a few emerging technologies will provide new capabilities with potential for transformative impact on society. Mills and Ottino [2] name pervasive wireless communication, big data and smart (additive) manufacturing as the three major emerging technologies. We agree. However, we believe that in addition to these three, bio-inspiration will lead to new scientific and engineering innovations with potential for equally large impact on society.

Wireless technologies are already prominent throughout both developing and developed countries. "Right now, a Masai warrior on a mobile phone in the middle of Kenya has better mobile communications than the president did 25 years ago. If he is on a smart phone using Google, he has access to more information than the U.S. president did just 15 years ago." [3] Big data is now recognized by the government and industry as critical to both operations and future planning. "…the world contains an unimaginably vast amount of digital information which is getting ever vaster ever more rapidly. This makes it possible to do many things that previously could not be done: spot business trends, prevent diseases, combat crime and so on." [4] The ages-old approach to manufacturing could be up-ended through new capabilities to 'print' whole 3D objects through Additive Manufacturing. In contrast to traditional manufacturing approaches such as milling and lathing that are inherently subtractive, additive manufacturing is a group of emerging technologies that creates objects from the bottom-up by adding material one cross-sectional layer at a time. This is conceptually similar to creating an object using building blocks or Legos®. [5] Finally, there remains a significant potential to design materials, devices, and systems based on millions of years of evolution of biological organisms that have experimented with different optimization solutions to difficult problems with complicated high-dimensional objective functions and constraints. While earlier adoption of nature's secrets focused on simple systems, e.g., Velcro™, current researchers are looking into more complex systems such as how to design sensors through echolation studies of bat ear shapes. [e.g.,6]

In the following sections we make an assessment of these four emerging and disruptive technologies, as well offer as insights on their ethical implications. Finally, we offer guidelines on how one can identify future disruptive areas (*aka,* Black Swans [7]). The world will continue to be influenced by science and technology. Wise use of existing technologies - as well as anticipation, development, and implementation of new technologies - is critical as we move into the 21st century.

EMERGING AND DISRUPTIVE TECHNOLOGIES

Wireless Enablement of "Just-In-Time Learning"

Wireless technologies are becoming prolific. Even in developing nations, the most sophisticated wireless systems are deployed, enabling rapid changes of economic and social status of traditionally underdeveloped regions. In regions that have historical low levels of education and training, wireless technology has permeated. For example, new applications such as wireless banking have circumvented the ramped corruption in many regions, including Afghanistan, to allow for loans and payments to be made safely and securely. Some of the emerging applications made possible by emerging wireless technologies include:

- Telemedicine and health care monitoring
- Remote education
- Public safety monitoring and data management
- Micro loans and banking
- Distributed markets for agricultural goods

In addition, a new area called machine to machine (M2M) communications has begun to emerge and is bringing with it new applications such as

- Environmental sensing, including the sensing of pathogens and water quality
- Sensors for agricultural management and soil evaluation
- Energy and transportation management
- Device and infrastructure maintenance

Nevertheless, as the complexity of technology and society increases, so must the simplicity of operation increase to counter the complexity of using new technology. To illustrate this principle, consider the case of a remote and poor village which has acquired a water pump that provides running water. What happens if this equipment breaks? Who in the village would be able to fix such a device? Certainly one might be able to download the technical manual for the pump given the rapidly growing capabilities of the wireless Internet, but what if the population is virtually illiterate? How can people with limited training and education deal with newly available sophisticated technologies? A new killer app to address this situation is the emergence of augmented reality for providing just-in-time education. This application has the ability to provide knowledge to the untrained individual to execute complex tasks in an easy and efficient manner.

The basic idea of augmented reality is to superimpose a computer generated image on a true-life image and thereby provide supplemental information of the environment being viewed. Simple augmented reality applications are beginning to appear now, where information about shops and restaurants might be superimposed in the view of a cell phone in camera mode pointed down a city street. Such versions of augmented reality are quite primitive, but still challenging from a technical perspective. Future wireless innovations can greatly improve the sophistication of augmented reality.

Back to the example of the broken pump; consider a hypothetical water pump that has augmented reality capability. A pump when viewed though the video camera of a cell phone would provide visual computer generated cues to the repairman. For example, the repairman could receive basic information on how to compress a c-clip, a tricky step in the repair of a pump.

There are several innovations that are in the works and some that have yet to be started that can enable this application. Clearly, high speed data transmission is needed - 4G cellular wireless systems such as long-term evolution (LTE) standards are beginning to be deployed and will improve in data rate and overall network capacity over the years. Still, these wireless links were designed with the assumptions behind today's applications, i.e., that more data flows from the network to the user device than vice versa. This application is contrary to that assumption in that large volumes of information flow from the user device to the network, this volume of information is considerable, and hence the need for local area communications instead is motivated. Such technology will require the fusion of macro-cellular high data rate systems with local, perhaps object-located communications. Recognition of the image and precise alignment of the augmentation is challenging. Image processing techniques are the standard approach today, but highly precise short-range radio location technologies could greatly simplify this task.

The social ramifications of this technology are immense, changing semi-skilled or unskilled laborers into skilled laborers able to perform complex tasks by calling on the intuitive interface made possible by high speed wireless data. It is a technology that can speed the adoption of wireless, as well as improve the productivity factor of those with limited training and education.

Big Data

The era of big data is upon us. From petabytes of scientific data repositories, we are now increasingly encountering exabyte-scale problem domains, e.g., in astrophysics, mobile data traffic, and digital libraries. Multiple domains, across sciences, engineering, and humanities, are now benefiting from the "big data rush."

One of the emerging areas in this space is social media analytics. Modern communication forms such as social media and microblogs are fueling new data-driven methods by which we can comprehend, and even influence, the progression of events [8,9]. Tracking sentiments of people via "massive passive" data (e.g., tweets; [10]) has been shown to very accurately shed light into the collective emotional states of individuals, with remarkable consistency across countries, languages, and time zones. Sites such as Google FluTrends (http://www.google.org/flutrends/) aggregate health-seeking behavior of people from search queries and aim to track the spread of diseases across the globe. Researchers are turning to micro-blogging as a strategy to predict elections, stock markets, box office returns, and populist uprisings.

A second area benefiting from data analytics methods is intelligence analysis. Intelligence analysts today are faced with many challenges, chief among them being the need to fuse disparate streams of data, and rapidly arrive at analytical decisions and quantitative predictions for use by policy makers. One of the emerging trends is to use open source data to capture population-level changes in communication patterns and content and use such trends to generate alerts about social, economic, and political phenomena. Data analytics methods are now being integrated with model-based approaches to create entire systems for predicting strife, social unrest, and events such as the "Arab Spring." Parallel to Google FluTrends mentioned above, systems such as GlobalIncidentMap (www.globalincidentmap.com) and Ushahidi (www.ushahidi.com) aim to serve as conflict early warning systems. Since the Egypt riots, a few papers [11] have emerged that claim to have anticipated or predicted the happenings.

A third example of big data in action can be found in the areas of sustainability modeling and characterization. Infrastructures ranging from IT, energy, transportation, water, and other domains are being revisited holistically from a sustainability perspective. Sustainability is a difficult goal to achieve, because the systems under consideration comprise complex, interconnected entities about whom first principles modeling is intractable. Therefore data-driven methods hold significant promise. They enable us to model not just individual subsystems but also help achieve an end-to-end holistic understanding of the overall system using methods such as life-cycle assessment [12]. It has been predicted that smart grid data analytics will reach 4.2 billion dollars in revenue by 2015 [13].

Finally, there is now an unprecedented push to incorporate information technology into health care at a more fundamental level. The current challenge in the field is to harmonize diverse collections of data and analyze them with methods that allow extracting new, non-trivial, and non-obvious knowledge about patient(s), condition(s), and even entire healthcare establishments. Many health care providers have proven that electronic medical records (EMR) data mining can lead to delivering quality healthcare at significant (one-third) cost savings. These cost savings can accrue in multiple ways: in improving the efficiency of healthcare delivery by optimizing hospital routing systems; by identifying correlations between drug usage, social history, external factors, and inadvertent side effects leading to better warning systems; and finally to augment physician diagnoses of critical conditions by serving as clinical decision support systems.

It is clear that data analytics and knowledge discovery research will continue to permeate modern science and engineering disciplines. Its potential for disruption is manifest in many of the above examples. (For instance, Google FluTrends is an example of such a technology that completely bypasses the currently costly form of painstaking data collection from primary care providers/health centers and simply aggregates queries from consumers directly.) As big data techniques penetrate more traditional disciplines, aspects that will become relevant include ensuring privacy-preservation and control of disclosure, fusing inferences from multiple sources, and integration of model-driven and data-driven methods.

Additive Manufacturing

Traditional manufacturing processes (*e.g.*, machining, casting, molding, stamping) are based either on subtractive processes (where objects are created through the subtraction of material from a workpiece) or tooling (where objects are created by forming around a pre-fabricated tool). The geometries, materials, and functionality of final products are limited by the capabilities of the tools used in these manufacturing processes.

Additive Manufacturing (AM) is a group of emerging manufacturing technologies that create objects from the bottom-up by adding material one cross-sectional layer at a time [14]. The basic steps of AM are shown in Fig. 1. AM begins with a three-dimensional solid model of the object, typically created by computer-aided design (CAD) software, or a three-dimensional scan of an existing artifact. Then, specialized software slices the solid model into cross-sectional layers. Next, the prepared computer file is sent to the AM machine to create the object layer-by-layer, following the toolpath generated by the software. Each AM technology has a unique principal solution for forming each layer; ranging from jetting a binder into a polymeric powder, to precisely extruding a heated plastic filament, to using an electron beam to selectively melt metal powder [15].

Figure 1. Generalized Additive Manufacturing Process.

Additive manufacturing offers a number of benefits over traditional manufacturing techniques:

- *Digital design and manufacturing*: All AM processes create physical parts directly from a standardized digital file (.STL), which is a representation of a three-dimensional solid model. Creating the part directly from the computer model ensures that the created part precisely represents the designer's intent and thus reduces inaccuracies found in traditional manufacturing processes. In addition, the representation of physical artifacts with a digital file enables rapid global distribution of products, thus potentially transforming product distribution much in the same way the MP3 did for music. Furthermore, these computer-controlled processes require a low level of operator expertise, and can often operate unmonitored. This capability decreases the time to produce products, reduces the time between design iterations, and almost enables manufacturing at a distributed global scale.

- *Increased/free part complexity*: The layer-by-layer build process of AM provides systems the capability to create complex shapes that cannot be produced by any other means. For example, conformal internal cooling channels can be built into components without separate assembly post-processes. Fundamentally, AM processes allow designers to selectively place material only where it is needed. Taking inspiration from nature (*e.g.*, coral, wood, bone), designers can now create cellular materials–strong and stiff structures that are also lightweight (*e.g.*, Fig. 2).

- *"Single tool" process*: No matter the desired geometry, there is no need to change any aspect of the AM process. In effect, this makes shape complexity free—there is no additional cost or lead time between making an object complex or simple. (This is in contrast to metal casting and injection molding where a new product requires a new mold in which to cast the part; or in machining, where several tool changes are needed to create a finished product.) As such, AM processes are excellent for creating customized, complex geometries that cannot be economically offered by any traditional manufacturing process.

- *Waste reduction*: As material is added layer by layer, there is little to no waste in AM processes as only the material needed for the part is used in production. This lies in stark contrast to traditional subtractive manufacturing processes, such as machining, where the desired part is carved out of a stock billet—often resulting in much of the final product leaving behind wasted material chips.

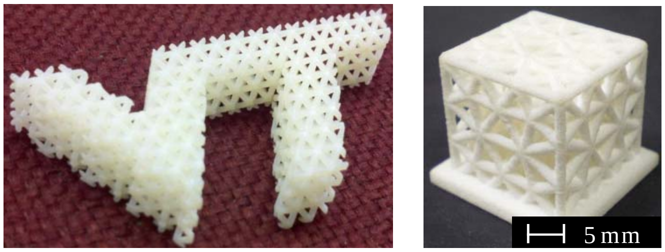

Figure 2. Complex (cellular) geometries created via Additive Manufacturing.

A 2010 Ganter report identified Additive Manufacturing as transformational technology in the Technology Trigger phase of the Hype Cycle (i.e., only 5-10 years from mass adoption). Those involved in AM research might argue that it instead is emerging from a "Trough of Disillusionment" towards a "Slope of Enlightenment." Industrial success stories of using AM for part production include:

- *Automobile components*: While AM is not yet suitable for mass production, it is increasingly used to create components for high-end, specialized automobiles. For example, engine parts for Formula 1 race cars have been fabricated using direct metal laser sintering.

- *Aircraft components*: Low-volume production found in the aerospace industry makes it another market primed for disruption from AM. While the parts resulting from direct metal AM processes are still not quite at critical components grade, there exist many instances of AM parts being used in aircraft. One example is an environmental control system duct on the F-18. The complexity offered by AM enabled the redesign of the assembly, and reduced the number of parts involved from sixteen to just one. Whereas the traditionally manufactured assembly must have its design tailored to fit the capabilities of the machine tools used to produce the part, the AM part is built precisely to fulfill its function.

- *Custom orthodontics*: Align Technology, Inc. uses AM to create clear, custom braces for hundreds of thousands of patients across the globe. Specifically, stereolithography is used to fabricate molds from 3D scan data of each patient's dental impressions. FDA-approved polymer is then cast into the molds to create the braces.

- *Custom hearing aids*: Siemens and Phonak apply laser sintering to quickly fabricate custom hearing aids. Based on 3D scans of impressions of the ear canal, the resulting hearing aid fits perfectly in the patient's ear and is almost hidden from view.

There are several aspects of Additive Manufacturing technologies that are potentially disruptive in many different contexts. With the ability to efficiently manufacture custom goods, it is possible that local manufacturing could start making a return to the United States. Thus, AM could dramatically reduce costs (both monetary and environmental) related to production, packaging, distribution, and overseas transportation. The digitization of physical artifacts allows for global sharing and distribution of designed solutions. It enables crowd-sourced design (and individual fabrication) of physical hardware. It democratizes manufacturing, which could allow anyone to become an entrepreneur. More broadly, digital distributed manufacturing will have significant impacts on global economic, intellectual property, supply chain, and export control policies.

Within the context of the mechanical engineering discipline, it is AM's relaxation of the design constraints imposed by traditional manufacturing that is the most promising. The complexity offered by AM allows a designer to strategically and selectively place material wherever it is needed most. Emerging AM systems can simultaneously deposit multiple material systems, thus enabling creation of functionally graded materials and the tailoring of the mechanical and material properties of each voxel of an artifact. By eliminating existing "design for manufacturing" constraints, AM will lead to the design and fabrication systems that are structurally tailored for their design intent(s).

In addition, AM may offer a novel new means toward the incorporation of NBIC technologies into prototype and finished products. Such an interdisciplinary approach could offer even greater design flexibility and higher part quality within AM-produced components. The marriage of AM and nanomaterials offers a particularly intriguing avenue for perhaps overcoming some of the fundamental materials and design limitations that presently stymie AM engineers and designers. Nanotechnology offers a novel approach for AM with its potential to both complement existing techniques and create wholly new nanocomposites [16]. Similarly, the convergence of AM with bioengineering technologies could further escalate AM's promise. In the past decade, significant advances have been made in using AM to "print" tissue scaffolds—biocompatible materials that, when implanted into the body and integrated with biological cells, assist in the regeneration of tissue. The geometric freedom offered by AM allows for the creation of scaffolds that are optimized to encourage cellular growth, while maintaining strength. In addition, recent advances have been made in direct printing of human tissue. These "bio-printers" could eventually permit the routine printing of replacement organs for transplant.

To realize the full potential of AM, engineers must not only understand its technologies and materials, they must also be able to synthesize its economic and environmental impacts on a manufacturing value chain. As such, researchers must continue to research novel AM processes, materials, and applications, as well as educate students in how to design products for AM.

Bioinspiration

While bioinspiration has been producing insights and technical devices of value to engineering for a long time already, it is still an emerging field that harbors a large untapped potential for disruptive technology. The engineering potential of biological model systems can be traced back to the unique properties and - in particular – the unparalleled scale of the evolutionary process that is responsible for all living organisms. In the course of evolution, an astronomical number of prototypes, i.e., individual organisms, have been evaluated for their fitness through extensive "testing" in the physical world. The scope of the resulting optimization process exceeds anything that would be possible in engineering. It has allowed biological evolution to explore solutions to difficult optimization problems with complicated high-dimensional objective functions and likewise complicated constraints.

As a result, many large performance gaps continue to exist between the capabilities of biological systems and those of related engineering solutions. These performance gaps are particularly common and significant in areas where a solution needs to be found for multiple objectives and under multiple constraints. This can be explained by the far superior capabilities of evolution with regard to finding optima in complicated search spaces. Hence, any disruptive impacts of bioinspiration are mostly likely to be found in areas of engineering science that deal with the integration of complicated systems rather than with the optimization of device functions for which the relationship between performance and design parameters can be readily understood.

While individual success stories of bioinspiration in engineering reach back many decades (e.g., Velcro [17]), a robust trend towards engineering applications of bioinspiration has only been detectable for about 30 years. This trend is evident, for example, in issued US patents that contain keywords such as "biomimetic" or "bioinspired" (Fig. 3, following an approach proposed in [18]). This data shows not only a rise in issued patents that contain these keywords but also a rise in the portion of patents that are linked to bioinspiration in this manner. Hence, the data reflects a genuine expansion of the role that bioinspiration plays in engineering innovation and not just the overall rise in issued patents that has taken place during the same period. However, the numbers obtained are not indicative of a major quantitative role for bioinspiration at the level of issued patents: In 2011, for example, 395 issued US patents contained language that suggested a role for bioinspiration. This corresponds to only 0.16% of the total number of US patents issued in that year (247,727). However, it should be noted that these numbers are likely an underestimate of the significance of bioinspiration, because describing the source of inspiration in a patent application is not commonplace, and in many cases it could have been done using terms that were not included in the current search. Nevertheless, this measure characterizes bioinspiration as growing trend in engineering that is still at the stage of an emerging technology at present.

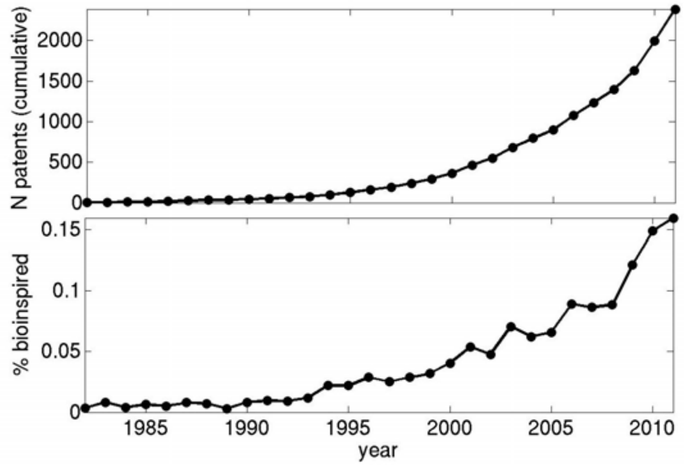

Figure 3. Growth in bioinspired engineering as evident from US patent filings. Top: cumulative number of patents issued that contained key words such as biomimetic, bionic, or various versions of "bioinspired" ("biologically inspired", "bioinspired", or "bio-inspired"). Bottom: portion of patents with keywords hinting a bioinspiration among all patents issued in the same year.

Hence, the question remains whether bioinspiration will eventually assume a significant role in engineering innovation as a major source of innovation. If this is feasible in principle, it could happen either through continued incremental growth or through a rapid transition in the field. The latter could occur if major impediments to the growth of bioinspired engineering existed and were to be removed suddenly. A look at past success stories in bioinspiration and the present state of the field yields evidence that the growth of bioinspiration is indeed held back by significant obstacles. For example, many important bioinspired engineering discoveries - such as Velcro – have been to a large extent gifts of serendipity. At present, no objective methods exist to identify biological model systems that could provide inspiration of value to engineering. Research in the field mainly consists of individual case studies. These research questions posed in these case studies are scattered widely in their biological model systems as well as in the targeted engineering areas. As a result, case studies remain separated by large interdisciplinary gaps that are difficult to bridge and leave present-day bioinspired engineering in the state of a severely fragmented research area.

A key factor that perpetuates this fragmentation is a lack of objective methodology that would be specific to bioinspiration. At present, the overwhelming majority of methods that are used in bioinspired engineering are specific to the biological, physical, and engineering aspects of the individual case studies, but not to bioinspiration itself. In order to mature into an engineering science in its own right, bioinspiration needs to develop its own specific theory and methodology that will then also serve as a bridge between all the research conducted in this area.

A possible way to improve this situation could be to adopt fundamental principles and approaches from biology for use in bioinspired engineering. Like bioinspired engineering, the life sciences also consist of a highly diverse range of research directions and methods. However, all these varied directions in biology are bound together by the concept of evolution. Irrespective of the biological system or the physical context under study, all traits of living organisms can be explained from their evolutionary history in one way or other, e.g., as an adaptation or perhaps as an evolutionary relict. Because of the central position of evolution, it is very common for biological research to include an evolutionary viewpoint and it would not be difficult to add such a view point to many of the other studies in a meaningful manner.

An important outcome of evolution that is likewise central to many areas of the life sciences is biodiversity. Evolutionary processes such as "adaptive radiations" have created groups of biological species that represent different variations of a common principle. Examples of far-reaching adaptive radiations are the approximately 400,000 species of beetles, which account for about 40% of all described insect species [19]), and the approximately 1,200 different bat species, which account for about 20% of all mammalian species. In the latter case, it is noteworthy how this biodiversity originated during a "big bang" event of rapid evolution during the Eocene [20]. In biology, comparisons within and between such species groups are frequently used to help in the interpretation of biological adaptations in a "comparative approach".

This evolutionary framework and in particular the outcomes of adaptive radiations could also play an important role in developing the field of bioinspired engineering into a major contributing force behind engineering innovation. Assuming an evolutionary perspective can help to put information on biological model systems into context, can establish links between different model systems, and can guide the selection of future model systems. Most importantly, biodiversity can be viewed as an additional level of biological organization that could be mined for inspirations and insight of potential value to engineering. In particular, looking at biological systems and their function at the biodiversity level could provide information on how a general principle could be adapted to deliver high performance in various tasks and under varying sets of constraints. If objective rules for the formalization of such adaptations could be extracted from biodiversity, they could be used in the design of customized technology. Knowledge on this process mined from the diversity of solutions found in nature could hence give rise to more flexible and adaptive technologies that through these properties could have a profound impact on engineering and human society.

To realize this potential of the biodiversity, bioinspired engineering needs to develop methods to generate large amounts of quantitative data across large ensembles of biological species. It also needs to develop big-data analysis methods for the extraction of evolutionary adaptation "rules" from such data. The fundamentals of such methods would not be specific to any particular biological model system and could hence provide a common methodology for any kind of bioinspired engineering science. In the course of the development of these methods, a theoretical basis for bioinspired engineering could also be derived from the evolutionary/comparative framework of biology. Once bioinspired engineering is equipped with such a theoretical basis and methods, it could transform itself into a mature scientific/engineering discipline with objective methodology as well as the high-degree of formalization and automation that have played key roles in the advancement of other engineering disciplines.

In order to make progress towards this goal, current engineering researchers need to reach out to biologists who can help them integrate these concepts (biodiversity, evolutionary mechanisms and in particular adaptive radiations) into their research. They also need to find data sources for quantitative data on biological form and function across large number of species. The extensive research collections of natural history museums could assume such a new function as data mines for the search of new engineering principles, if ways are found to digitize and to analyze their specimens in efficient and meaningful ways.

Finally, the progress of bioinspired engineering will also depend on novel interdisciplinary collaborations in education. Engineering students with an interest in the area should have access to curricula that emphasize the basic biological concepts and integrate them well with related engineering concepts and theoretical tools such as optimization theory. The result of such curricula will be engineers who are well-versed in the application of biological concepts and who will hence be in an excellent position to develop an integrated theory for bioinspired engineering.

CULTIVATING BLACK SWAN TECHNOLOGIES

In his book, "The Black Swan" [7], the New York Times best-selling author, Nassim Nicholas Taleb defines a Black Swan as an event that has three characteristics: it is an outlier; it carries an extreme impact; and it has retrospective predictability. He further makes a claim that our world is dominated by Black Swans. He cites examples of three recently implemented technologies that most impact our world today - the Internet, the computer, and the laser - and notes that all three were unplanned, and unpredicted, and remained surprisingly unappreciated well after their discovery, before taking the world by storm. Wikipedia defines Black Swans as “The disproportionate role of high-impact, hard to predict, and *rare* events that are beyond the realm of normal expectations in history, science, finance, and technology.” However, three recent events—the real estate meltdown/collapse of the stock market in late 2008; the “Arab Spring” in January 2011; and the earthquake, tsunami, and nuclear accident in Japan in March 2011—suggest that Black Swans may not be so rare.

The next Black Swan, at least as defined by Taleb, may not be predicted, but it is our belief that we can create an environment and a breeding ground for future positive Black Swans - an environment in which engineers, scientists and humanists from different disciplines can come together to move beyond the predictable and incremental advances in current technologies to the transformative science and technology of the future. For example, at the Virginia Tech-Institute for Critical Technology and Applied Science (ICTAS), a monthly “Black Swan” Seminar is held in which engineers, scientists and humanists come together to explore the next potential disruptive/ transformative technologies.

Appropriately, the seminar series is held in ICTAS's Café X where a free-flowing and unencumbered exploration of "X, the unknown" is the expectation. Facilitated by a researcher, a seminar generally focuses on a broad field of inquiry and is triggered by the question, "What technology/innovation/idea will transform your field in seven years? Or by a more in-your-face question, "What advances in your field will make you unemployable/irrelevant in seven years?" The participants are generally spared the tyranny of PowerPoint. Instead, visuals such as scribbled notes on napkins, physical artifacts, or conceptual images of the future are the norm. Typically, a few cygnets are hatched which are then nurtured with the hope that one or more of these will develop into the next transformative technology. These seminars are open to all who want to innovate and stay ahead of the times.

For a systematic pursuit of the next disruptive technologies, there is a need to develop and promote such seminars or similar mechanisms with an emphasis on unencumbered, high-risk, high reward discovery. There is much to be gained in forging and strengthening the current weak and somewhat tenuous bonds among seemingly disparate disciplines. Innovation and creativity have often been a by-product of these ties.

SOCIETAL AND ETHICAL CONSIDERATIONS

The confluence of the converging and emerging technologies discussed above is poised to spur inventions and knowledge to create opportunities for new industries, robust job growth, and enhanced human capabilities. However, technology’s progression is also filled with instances of errors and unintended consequences (as with DDT-**d**ichloro**d**iphenyl**t**richloroethane, genetically modified crops, and Chernobyl), resulting in a public suspicious of new technologies and technologists. There is also a perception that technology is “out of control” and that, too often, societies don’t have the ability to orchestrate a responsible development of powerful technologies that have the potential for huge economic development. This has undermined the confidence of the public in the power of technologies to solve problems and improve their quality of life [21].

Another dimension of this perception is that the majority of the public does not have a firm grasp of basic scientific facts and concepts. These findings from a report issued by the National Academy of Engineering (NAE) and the National Research Council (NRC) are reinforced by another 2001 survey conducted by the International Technology Education Association (ITEA) that revealed that "adults are very interested in but relatively poorly informed about technology" [22]. Also, too often engineers and scientists work in isolation and don’t engage the public in an effective dialogue. In the absence of such a meaningful dialogue between the scientific/engineering community and public on the potential pros and cons of the new technologies, the public generally ends up forming its opinion based on the headlines in the media and sometimes popular science fiction. In a science fiction book, "Prey" by Michael Crighton [23], a swarm of nanoparticles goes astray and starts hunting human beings. The book reinforced the perception that there are lurking dangers of nanotechnology that technologists have not shared with the public. In yet another nanotechnology gone-astray scenario, it was posited that sub-microscopic machines designed to share intelligence, but capable of replicating themselves without human intervention, could crowd the skies and devour the planet. Prince Charles raised the specter of this "grey goo" scenario and called for a moratorium on further development of nanotechnology [24].

The NSF and other federal agencies seem to be cognizant of the changing public perception. For example, in the NSF Report on NBIC [1], the authors specifically stress the need to address ethical, legal, and moral issues while experimenting with emerging technologies for improving human performance. In some quarters, it is considered unethical to halt the development of these technologies until all unanswered questions about the socio-environmental impact are answered. Consider, for example, the following quote from Philip J. Bond, US Under-Secretary of Commerce [25].

> "Given nanotechnology's extraordinary economic and societal potential, it would be unethical, in my view, to attempt to halt scientific and technological progress in nanotechnology. Nanotechnology offers the potential for improving people's standard of living, healthcare, and nutrition; reducing or even eliminating pollution through clean production technologies; repairing existing environmental damage; feeding the world's hungry; enabling the blind to see and the deaf to hear; eradicating diseases and offering protection against harmful bacteria and viruses; and even extending the length and the quality of life through the repair or replacement of failing organs. Given this fantastic potential, how can our attempt to harness nanotechnology's power at the earliest opportunity – to alleviate so many earthly ills – be anything other than ethical?"

However, given the souring public perception of new technologies, a rush to develop and deploy these disruptive technologies without due considerations to societal and ethical considerations is troublesome. Based on our experience of engineering education and profession, we believe that we don't do an adequate job in training our engineers to integrate the societal and ethical considerations as essential factors in the development and/or adoption of new technologies. In fact, our traditional engineering curriculum falls woefully short of even introducing students to the emerging technologies. Although students and practicing engineers are familiar with the ethos "Do No Public Harm," they are not well-trained to handle the complex ethical issues that may arise with the introduction of new technologies. Finally, we believe that as engineers and scientists, we do not engage the public effectively to increase awareness of emerging technologies. It is time for engineers to start building bridges again – the bridges to effective communication, mutual understanding, finding common objectives, and reaching for sustainable, holistic solutions to human needs.

Fisher and Mahajan [26] presented similar arguments and made a case that the curriculum must be liberalized with the goal of producing Humanistic Engineers – 21st century engineers who are able to initiate and engage in effective dialogue with non-technical audiences regarding socio-humanistic critiques of engineering processes and products, and who are able to adopt multiple perspectives and to become their own socio-humanistic interlocutors. To this end, they suggested that such a curriculum should integrate technical and humanistic perspectives *in both directions* in a truly multidisciplinary fashion, drawing from innovative collaborations that reflect the continuous and interconnected fabric of the real world, and take full advantage of the limited time already devoted to the humanities, arts, and social sciences, coordinating them with engineering education objectives but without compromising their disciplinary integrity. They cautioned that to be effective, the "non-technical" components of a Humanistic Engineering curriculum need to go beyond existing attempts that, for whatever reasons, neither represent nor engage engineering perspectives. Otherwise, this component all too easily becomes little more than a counterproductive conscience, lacking convincing authority in the eyes of technical students and reinforcing traditional stereotypes that are carried into professional life. The authors did not outline an ideal curriculum incorporating these principles but presented a few initiatives taken at the University of Colorado, Boulder to integrate some core concepts in teaching and research. These included multidisciplinary, collaborative courses on, "Technology and Culture", a lecture and seminar series on "Dialogues Between Two Cultures", an "Earth Systems Engineering" initiative, and the founding of the student organization, "Engineers without Borders," among others.

Looking ahead, there is a need to develop and implement undergraduate engineering curriculum that introduces students to the emerging technologies—their impact and the associated complex societal and ethical dimensions. It should weave societal, humanistic, environmental, and leadership contexts and considerations into the technical curriculum itself. As stated above, the goal is largely to reflect practical conditions in order to increase the likelihood that engineers are, at the very least, responsive to non-technical demands and scrutiny and, ideally, are able to consider and take into account such issues and perspectives on their own.

Similar considerations apply in the context of graduate education and research. The focus should be on moving beyond the silo-based education and research and moving the academe to integrate interdisciplinary inquiry and approach in both the discovery and the learning domains. Initiatives like Black Swan seminars should be undertaken to promote dialogue among engineers, scientists, humanists and public for an upstream understanding of the societal and ethical issues that may arise with the potential disruptive technologies of the future, and midstream modulation in engineering design and development as a means to promote reflexive participation by engineers and scientists in the social shaping and governance of technology.

NOMENCLATURE

AM – Additive Manufacturing
CAD - Computer-Aided Design
DOC – Department of Commerce
EMR – Electronic Medical Records
IT – Information Technology
ITEA - International Technology Education Association
LTE – Long-Term Evolution wireless standards
NAE - National Academy of Engineering
NBIC – Nanotechnology, Biotechnology, Information technology, and Cognitive science
NRC - National Research Council
NSF – National Science Foundation

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