Bioengineering

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Abstract

In this entry, the field of bioengineering will be discussed, including the large field of biomedical engineering and the nonmedical fields of biosystems and bioprocess engineering and biomimetics. The focus is on ethical issues in bioengineering. Associated ethical issues include clinical-related issues concerning manipulation of the human genome, the development of prosthetic organs and limbs, engineering of the human brain and nervous system, and human enhancement. In the nonmedical fields, there are ethical issues concerning agriculture, food production, environmental risks, and dual use.

Keywords

Biomedical engineering; Tissue engineering; Prostheses; Imaging; Neurotechnology; Agriculture; Food; Biofuels

Introduction

Bioengineering, also called biological engineering, is a field that combines the concepts, principles, and methods of engineering and biology. In this field, knowledge of living systems is combined with engineering principles to yield useful applications, most of them in the medical and life sciences. The term "bioengineering" is sometimes held to be synonymous with biomedical engineering. More frequently, though, bioengineering is defined to include biomedical engineering, but also other forms of biological engineering. This wider definition will be used in this entry.

Biomedical engineering is the application of engineering principles and techniques to medicine. It combines expertise in engineering with expertise in medicine and human biology to develop technologies and techniques for healthcare and patient care. Biomedical engineering constitutes a large part of the field of bioengineering. The remainder of the field is constituted by those areas in which biology and engineering are combined in fields which are not, or not predominantly, medical. These include application areas in agricultural and life sciences, environmental engineering, biologically inspired design, and fundamental research at the intersection of engineering and biology.

The term "bioengineering" was coined in the 1950s, and the first bioengineering programs originate from the late 1960s. Bioengineering

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has part of its historical roots in agricultural engineering and biotechnology and another part in the development of medical electronics in the 1950s and 1960s. Bioengineering has been booming in recent decades, in part because of major advances in genetic, molecular, and cellular engineering. Because it is a relatively new field, there is currently no distinct academic field of bioengineering ethics. Ethical issues in bioengineering are currently studied in bioethics, medical ethics, and engineering ethics. Yet, professional ethical issues in bioengineering and biomedical engineering are often different from the ones traditionally discussed in these fields of ethics, since the combination of biology, medicine, and engineering yields new issues and challenges.

Principles of engineering ethics apply to bioengineering, as a form of engineering, but bioengineering raises significant additional ethical issues that concern the engineering of biological organisms and materials and the study, diagnosis, and treatment of patients. Bioethics and medical ethics provide a large part of a vocabulary to approach these additional ethical issues. However, at the intersection of engineering, biology, and medicine, qualitatively new ethical issues emerge, such as issues concerning human enhancement, genetic modification, and biomimetic robots that are not covered in traditional bio-, medical, and engineering ethics.

It is fair to say, though, that the ethical responsibilities of biomedical engineers combine those of engineers and biologists or medical professionals, including a responsibility to adhere to general ethical standards in research and development of technology and to do R&D that adheres to the specific standards set forth by medical ethics and bioethics. Although biomedical engineers are not medical practitioners, one could understand them as indirect practitioners, since the technologies and techniques they develop co-determine medical practice. In bioengineering, a distinction can be made between ethical issues in the R&D practice and ethical issues regarding the implications of developed techniques and devices for their intended domains of application. Within R&D there are ethical issues regarding human and animal experimentation, the use and modification of biomaterials, as well as general issues of R&D ethics like truthfulness and the avoidance of conflicts of interests. Regarding the intended domain of application, bioengineers have a responsibility to anticipate the consequences of their technologies for society and to ensure that technologies and techniques are designed in a manner consistent with and supportive of accepted ethical principles.

Besides ethical issues that concern the professional practice of bioengineers, there are also larger ethical issues that concern the social role and impact of bioengineering. Some key issues are the risks involved in bioengineering for health, safety, and the environment, issues of dignity and privacy, and, particularly in a global context, issues of justice and benefit sharing. The normative questions posed by bioengineering are therefore not only relevant to bioengineers but also to users (clinicians, patients, consumers) and to society at large. Thus, a broad normative discussion is needed concerning ethical aspects of the values and goals of bioengineering, its methods and practices, and applications, usage, and effects on stakeholders and society at large.

This discussion will be different in different societies and cultures. Different cultural, natural, and social environments come with different values as well as different understandings of how body, mind, and world interact (Crafa and Nagel 2015) which lead to different moral evaluations. In particular, non-reductionist approaches to the human person, which are particularly well represented in many non-Western societies, may conflict with the predominantly reductionist and materialist approach of bioengineering because of religious objections or perceived risks to the person.

Of the following six sections, the first four will focus on ethical issues in biomedical engineering (sections “Cellular, Genetic, and Tissue Engineering”; “Biomaterials, Prostheses, and Implants”; “Biomedical Imaging and Optics”; and “Neural Engineering”) and the final two sections will focus on ethical issues in nonmedical areas of bioengineering (sections “Biosystems and Bioprocess Engineering” and

"Biomimetics"). The first four sections will each discuss ethical issues in major areas of biomedical engineering, including cellular, genetic, and tissue engineering (section "Cellular, Genetic, and Tissue Engineering"), biomaterials and prosthetics (section "Biomaterials, Prostheses, and Implants"), biomedical imaging and optics (section "Biomedical Imaging and Optics"), and neural engineering (section "Neural Engineering"). Section "Biosystems and Bioprocess Engineering" will then focus on the large fields of biosystems and bioprocess engineering, and section "Biomimetics" will analyze ethical issues in biomimetics.

Cellular, Genetic, and Tissue Engineering

Modern biomedical engineering centrally involves these three fields, which include recent attempts to approach biomedical problems at the microscopic level. *Cellular engineering* aims to control cell function through chemical, mechanical, electrical, or genetic engineering of cells. It attempts to understand pathological processes at the cellular level and to intervene by means of miniature devices that stimulate or inhibit cellular processes at target locations to prevent or treat disease. *Genetic engineering* is a form of cellular engineering that specifically aims to control the genetic material in cells. Most of biomedical research in this area is focused on *somatic cell therapy*, which is the genetic modification of bodily cells other than sperm or egg cells in order to replace defective genes with functional ones. Such therapy is being clinically tested to treat inheritable diseases, cancer, diabetes, and various neurodegenerative disorders. Somatic cell gene therapy to treat serious diseases currently does not raise serious ethical issues.

Germline engineering, the engineering of reproductive cells, is a more controversial practice in which genes in eggs, sperm, or very early embryos are modified. This topic is being studied for future application, with some pilot applications having taken place. The moral controversy is caused by the fact that it results in inheritable modifications of the genome that are passed on to future generations. The long-term side effects of such engineering are currently unpredictable, and there are also concerns that such engineering violates the rights of future generations or amounts to "playing God." A particular controversy has erupted surrounding the birth of "three-parent babies" in the UK, in which germline engineering took place to repair defective mitochondrial DNA in a woman's eggs by replacing it with DNA from another woman's eggs. A related controversial practice is that of genetic enhancement, which is the genetic engineering to enhance human traits such as intelligence or muscle strength. It can be practiced on somatic cells or germline cells. Genetic enhancement is controversial because some argue that it is unnatural and socially and morally undesirable to modify human biology to create humans with superhuman abilities, while others argue that this is the natural way of progress that we should endorse.

The third field to be discussed here, *tissue engineering*, is aimed at restoring, maintaining, and improving the functioning of tissues or whole organs by means of biological substitutes that repair or replace these tissues or organs. One of the goals of tissue engineering is to create artificially grown organs for patients that need organ transplants. Tissue engineering strongly depends on cellular engineering as well as on biomaterials science. A main area of moral controversy in tissue engineering is related to the source of the cells that can be obtained from humans (autogenous or allogenous) or xenogeneic, from other species. The use of *xenogeneic* (animal or vegetative) *cells* and *human embryonic tissue* (stem and germ cells) poses different ethical questions. The use of xenogeneic cells and cell material is controversial because species boundaries are crossed in the process: it involves the creation and medical use of cells and tissues that, by origin, are part human, part animal or plant. The use of embryonic tissue is controversial because cells are harvested from human embryos, which are destroyed in the process or from aborted fetuses. It has been objected that it is unethical to kill or destroy human embryos and therefore it is also unethical to have a medical practice that involves it, and there are worries that a demand for human embryonic tissue promotes the large-scale cultivation of human embryos specifically for this purpose (De Vries et al. 2008). It will be a topic for future debate whether and if yes for which purposes biological materials from the different sources are allowed to be used; will it only be for life-threatening cases or also for rather mild therapeutic cases such as tooth regeneration?

Moral controversy in tissue engineering has also extended to its use of therapeutic or research cloning. Objections have been raised to the creation and destruction of human embryos for research purposes. In addition, it is feared that permitting therapeutic cloning may facilitate acceptance of reproductive cloning. Another ethical issue in tissue engineering is how to balance the prolonging of life with the quality of life. To what extent should lengthening the life span of humans be a goal of tissue engineering, and how should such a goal be balanced against the goal of improving the quality of life, as these goals may sometimes conflict? Finally, patenting also raises ethical questions in tissue engineering: should it be possible to patent specific types of tissues, and if so, how should this be arranged? There are also several ethical issues surrounding the donation of cells and tissues for tissue engineering by human donors. Should, for example, such donors be able to profit from the use of their cells or tissues? In nearly every country, this is currently not the case. Do donors have a right to informed consent for every use of their cells? In most countries, this is currently the case. And what right to privacy do donors have, and how can their privacy be safeguarded? Tissues of donors are stored in so-called biobanks, which are repositories for the storage of biospecimens that are used for clinical or research purposes. Public and private organizations that own such biobanks are responsible for protecting the privacy and confidentiality of donors, but there are different views on the extent and manner to which this should be done.

Biomaterials, Prostheses, and Implants

Biomaterials are synthetic or, more rarely, biological materials used in medical devices to repair natural tissue that was damaged by trauma or disease. Biomaterials research embraces the field of tissue engineering that aims at the growth or regeneration of organs and other biological materials and at fabricating functioning organs out of living cells, such as liver or skin cells, and that raises specific ethical concerns as discussed above, in section "Cellular, Genetic, and Tissue Engineering."

Biomaterials allow interactions between materials and biological tissues that increasingly well satisfy biocompatibility, functionality, and durability. For the development of biomaterials, the fields of basic materials science, research on biocompatibility, implant device development, surgical applications, and failure analysis have to work hand in hand to reduce the complication rate and improve clinical outcome. One core challenge is to understand and handle the natural tissue responses to materials. Coating medical devices such as artificial heart valves, vascular prostheses, coronary artery stents, catheters, hip and knee implants, intraocular lenses, and various other prostheses calls for a synthetic substance that fully (or at least satisfyingly) resists the body's natural attack response to foreign objects. Verifying implant vascularization makes use of imaging techniques that allow in vivo evaluation of tissue responses to biomaterials for performance and safety. Here, the close relation between different subfields of bioengineering gets evident.

Biomaterials find applications in uncountable medical devices and thus make an important contribution to the field of prosthetics. Prosthetics is concerned with the development and fitting of artificial body parts. Any artifact used to restore bodily functions can be conceptualized as prosthesis. A large number of human biological functions can be restored or improved with the aid of prostheses. The list of implants and related devices is extensive, as can be seen in this updated list from Brey (2014):

- Artificial limbs, including robotic ones and ones with sensory feedback to the body
- Artificial joints, hips, and vertebrae
- Artificial muscles made of polymer
- Artificial skin used to promote healing
- Artificial bone used to help heal fractures and replace diseased bone
- Bracing systems, cervical implants, and spinal cages to support the spine
- Silicone or plastic implants to build bony structures of the face
- Breast implants
- Penile implants
- Dental implants and false teeth
- Speech synthesizers and artificial larynxes to restore speech
- Retinal implants (experimental), intraocular lenses, and artificial corneas to restore vision
- Cochlear implants that replace the inner ear and involve a microphone, speech processor, and wiring to the nervous system
- Artificial nerves (experimental)
- Cardiac pacemakers, defibrillators, artificial heart valves, and heart-assist pumps
- Artificial hearts (experimental)
- Artificial livers (experimental)
- Artificial blood vessels and urological systems
- Artificial blood (experimental)
- Implanted drug-delivery systems (experimental)
- Artificial tracheas
- Electrodes implanted in the brain to control seizures or tremor
- Implanted chips to locate persons or to regulate devices in "intelligent environments"
- Orgasmatrons (implants for women that produce orgasms; experimental)
- Artificial ovaries for in vitro maturation
- Spinal neuroimplants with handheld remote control to block pain signals
- Motor neural prostheses based on functional electrical stimulation systems, which stimulate motor nerves for movement, respiration, and bladder function
- Artificial hippocampi in the brain (experimental)

Although research in prosthetics is primarily aimed at restoring damaged human functions, there has been a growing interest in the augmentation of human functions. Human augmentation or enhancement is a relatively new field in bioengineering directed at developing prosthetic devices that augment normal function or prevent injury to function. Prosthetic devices can already replace many parts of the human body, and revolutionary developments in bioengineering are rapidly expanding the reach of prosthetics. Biomedical engineers and medical specialists have a special, professional responsibility in dealing with the ethical issues that arise as a result, as they are primarily responsible for the development and fitting of prostheses.

The miniaturization of materials achieved by micro- and nanoscale science and engineering is another rapidly expanding, highly promising field that leads to clinical benefits in various fields. Lab-on-a-chip devices, which are miniature systems capable of analyses that usually require an entire laboratory of instruments, can enhance patient outcome significantly. Nanophase implants, i.e., implants of materials with grain sizes under 100 nm and specific mechanical properties, enable increased tissue regeneration in comparison to conventional materials. Nanoparticles, microscopic particles less than 100 nm in size, can be used for a controlled drug delivery that controls how the drug is administered and releases the drug in the exact dosage at the right time to improve healthcare.

The ethical questions related to the use of biomaterials fabricated from artificial substances including metals, polymers, composites, and ceramics mostly concern questions of health and safety. The reaction of the human body to artificial substances can lead to unforeseen consequences. In particular, testing materials and devices in patients needs careful balancing of risks and benefits as the testing usually involves invasive interventions that are risky due to possible unknown reactions. Given the expected long-term usage of devices in the human body, long-term in vitro tests are necessary but pose problems themselves. Animal experimentation must be scrutinized as to whether animal models can be relevant for humans and thus could justify animals' potential suffering. Moreover, the just allocation of scarce resources, both nationally and in a global context, and conflicts of interest in particular given the involvement of industry that seeks for cost-effective, profitable applications are topics for ethical deliberation.

Another class of special moral concerns is raised in the areas of human augmentation or enhancement as in the case of cosmetic surgery, most prominently breast enhancement, or neuroenhancement in which the goal is not a treatment of a disease but an augmentation of healthy form or function (Nagel 2010; Parens 1998). Here, the questions about animal and human experimentation and the distribution of scarce resources involve a different weighing compared to cases of treatment in demonstrated clinical needs. Which costs – monetary and others – are acceptable for enhancement research and applications? Which augmentations does society want to support, and which ones to restrict? What are arguments for facilitating or constraining access to enhancement interventions? As technology develops and demands for materials and devices increase, not only the technical challenges need research but also the ethical and social dimensions require careful consideration.

Biomedical Imaging and Optics

Since the invention of x-rays in the nineteenth century, increasingly more sophisticated systems have been developed for imaging organic structures and processes in humans. Technologies utilizing the various interaction of light with tissue use ultrasound, magnetism, UV, and other radiology can locate, track, and explore molecules, cells, fluids, gases, and tissues to allow ever more detailed views into (living) organisms. Many applications of imaging technologies aim at image-guided intervention.

Imaging technologies range from atomic and nanoscale systems and fluorescence tagging of molecules to medical imaging of blood flow, blood vessels, and cardiovascular lesions, to computational systems for numerical image analysis, to noninvasive optical systems that provide real-time imaging of drug dispersal in the interaction with target cells, and to high-resolution nuclear magnetic resonance spectroscopy and (functional) human brain mapping.

Optical imaging, to name one example, uses visible light and the special properties of photons to obtain detailed images of molecules, cells, organs, and tissues. It is widely used in endoscopy for studying the digestive tract or for minimally invasive robotic surgery. Raman spectroscopy can observe vibrational, rotational, and other low-frequency modes in a tissue to determine properties of inorganic and organic materials, e.g., in drug-cell and chemical-skin interactions. Molecular imaging techniques can visualize toxicodynamics used for drug target identification and drug development. Other types of biomedical imaging technologies are optical coherence tomography used to image the retina or coronary arteries and diffuse optical tomography that can be used to monitor chemotherapy treatment progress by being able to identify a tumor and tracking its shrinkage during the course of therapy. Bioluminescence based on light-emitting enzymes can be used to image inflammatory response associated with infected implanted biomedical devices. One frontier in bioengineering is working on bioluminescence and near-infrared fluorescence to engineer complex biological systems with the ability to emit light.

A technology that will allow applications that may be controversial is optogenetics: it combines genetic engineering techniques and optics to control cellular processes. Exposing the brain with light only activates or deactivates the specific neurons that were made light responsive by a specifically selected gene. With this procedure it is possible to turn neurons either on or off with millisecond timing. Optogenetic approaches allow controlling distinct cell types within a region and thus provide a basis for targeted interventions. Applications are discussed for behaviors related to addiction, depression, and compulsions, but also for cognition and other areas of normal brain function. While optogenetics is a fascinating research tool that can be used to answer clinically relevant questions, it is conceivable that it will be used for nonmedical reasons, be it for enhancement purposes or for “mind control” by applying optogenetics in people’s brains and to control their behaviors by shining light on them. The unique risk profile of the still novel technology requires to sensitively consider cases of abuse.

Biomedical imaging promises to make diagnosis of disease more accurate and less invasive and to improve the understanding of disease. Generally, imaging technologies that allow the monitoring of brain activity pose specific ethical questions given the delicate nature of the organ investigated. Questions on how information obtained from brain imaging should impact healthcare and courtroom decisions and how private brain processes should still be in the future are raised in parallel to increasing accuracy of brain imaging technologies. Other questions relate to the research process such as the case of incidental findings in which the researcher, who is often not a trained physician and often does not have radiological training, finds an anatomical abnormality, a variation in activations, or a performance that lies outside an expected norm and needs to decide on what to disclose to the participant (Illes et al. 2004). Research often studies healthy participants, and incidental findings pose practical challenges and ethical dilemmas for researchers as to how to manage and communicate an incidental finding that might need urgent diagnosis or treatment or could stay without any effect. In any case, it is important to have guidelines on how to react in such cases and to discuss how to design the informed consent protocols for imaging studies.

Neural Engineering

Neural engineering is a broad, interdisciplinary field within biomedical engineering, working on a particular subfield of biological “material,” i.e., the neural system. Neural engineering applies engineering principles and neuroscience methods to analyze neurological functions and to design treatments for neurological limitations and dysfunctions. It includes the analysis of multiple levels of neuronal processes including single channels, single cells, tissues, whole animals, and human cognitive levels. Neural engineering aims at the understanding, monitoring, repairing, replacing, manipulating, and enhancing of neural functioning often with the goal of providing rehabilitative solutions.

The scope of neural engineering encompasses a wide range of fields such as brain-machine (computer) interfaces, neuromodulation, neural prostheses, neuro-rehabilitation, neurorobotics, and neuroimaging. The diverse topics of neural engineering overlap, and the tasks most often require interdisciplinary work to finally be able to better help people suffering after stroke, spinal cord injury, traumatic brain injury, or neurodegenerative disorders. Neuromodulation serves as exemplary for neuroengineering technologies as it involves different disciplines and is in itself a wide field of study encompassing numerous implantable and noninvasive technologies that interface with the nervous system through electrical, electromagnetic, chemical, or optogenetic methodologies with the goal of long-term regulation of neural activity.

Deep brain stimulation (DBS) is currently used to treat severe neurological disorders, Parkinson’s disease in particular, and is explored in treatment for severe psychiatric disorders like major depression. For DBS, a thin electrode, the lead, is implanted in deep brain areas which are stimulated via a small pulse generator, implanted under the skin near the collarbone. Intracranial cortical stimulation (ICS) is an invasive technology, in which an array of electrodes is placed over the cortex to deliver electrical stimulation. This intervention is used to treat severe forms of epilepsy, tinnitus, pain, depression, or stroke. The electrical stimulation of the vagus nerve that requires the surgical implantation of a device (one part under the clavicle, one part in the neck) that sends electrical signals along the vagus nerve to the brainstem is used to treat epilepsy and explored for the treatment of multiple sclerosis and migraine.

Other neuromodulation technologies are transcranial magnetic stimulation (TMS), and transcranial electrical stimulation (as transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS)) is a noninvasive technique for brain stimulation that applies small, localized electrical currents to the brain, either via a powerful magnetic field (as in TMS) or via scalp electrodes (as in tDCS). Those technologies can be employed to eliminate or alleviate some symptoms. Transcutaneous electrical nerve stimulation (TENS) stimulates sensory nerves via electrodes on the skin and is used to reduce both acute and chronic pain.

Another rapidly growing field in neuroengineering is focused on neural growth, neural repair, and neural tissue regeneration. Congenital, degenerative, ischemic, or metabolic disorders of the central or peripheral nervous system often lead to permanent and incapacitating brain damage, paralysis from spinal cord injury, and peripheral nerve damage. Spontaneous regeneration and repair is limited in the peripheral nervous system and even more in the central nervous system. Progressive deterioration as in Alzheimer’s disease, Parkinson’s disease, multiple sclerosis, multiple system atrophy, and amyotrophic lateral sclerosis needs approaches in nerve regeneration that poses a complex challenge. Recent advances in nerve regeneration involve the application of tissue engineering principles. There are advances in artificially creating tissue outside of the body to implant to the site of injury. Genetic engineering and tissue engineering develop 3D scaffolds to allow a regrowth of axons on-site. This endeavor is supported by research on bioartificial nerve guidance conduits that should facilitate the growth of neurons to allow regeneration of nerve injury and the regeneration of the spinal cord tissue after spinal cord injury. A frontier of neuroscience is to use the natural regenerative capacity of adult neurogenesis to control neuronal development.

While most efforts in neuroengineering target the treatment of diseases, there is considerable impact on employment of the technologies for neuro-enhancement. Neuro-enhancement is the use of technologies or prescription medication by healthy persons for the purpose of augmenting normal physical, cognitive, or affective function. In the last years there is growing interest by individuals without recognized dysfunction to augment their brain function. Enhancement interventions come in many varieties: there are manifold methods, goals, motivations, desires, ideals, and values that can invoke heated discussions (Nagel 2014). Today, the usage of prescription medication is the most prominent case for enhancement interventions, probably due to its perceived noninvasive nature. However, neuromodulation technologies such as tDCS are promoted as effective enhancement means, as are brain-computer interfaces.

Just as the monitoring of brain processes poses special ethical questions, so does the manipulation of brain processes. Interventions in the brain as central organ of personality, consciousness, and experiences have always raised hopes and fears, and prospects shall be balanced with concerns. Importantly, long-term studies are lacking, and the duration of effects is not yet known. Besides the insecurities of the risk and side-effect profile of focal neurostimulation, there are various ethical questions: Balancing of beneficence and non-maleficence is a central task for ethical deliberation that shall happen proactively. Questions of unwanted personality changes require scrutiny, as does the employment in vulnerable populations, such as in children, the mentally disabled, or the elderly, and the risk of coercion. How can innovations in invasive and noninvasive neurotechnologies be designed such that they contribute to well-being? Ethical questions go beyond purely individual reasoning and must consider normative questions related to the values that a society wants to promote. What are the relevant aspects to consider regarding self-determination, autonomy, and responsibility of the patient or consumer?

Biosystems and Bioprocess Engineering

Biosystems engineering integrates engineering science and design with applied biological, environmental, and agricultural sciences. Historically, the field stems from agricultural engineering and has since been broadened to all living organisms, with the exception of biomedical applications. It sometimes is also called biological engineering. It includes various related areas. A first area is bioresource engineering, which typically concerns the engineering of bioresources, which are organic substances that have a value for humans such as food, feed, energy, and shelter, such as fruit, vegetables, wood, algae, residual biomasses, and organic waste. Another area is bioenvironmental engineering, which is concerned with preventing and solving environmental problems related to human activity, including waste management, water management (including recycling and measurements of pathogens, chemicals, and other contaminants), environmental control systems for buildings and biological systems, pollution and air quality control and treatment, the evaluation of workplace hazards, and the design of environmental systems.

Third, agricultural engineering includes aspects of bioresource engineering, but also food engineering (including food processing and food safety), the design of agricultural machinery and structures (including irrigation and storage systems), soil management, livestock production, and the seeding, harvesting, and processing of crops. Another important area of biosystems engineering is the production of bioenergy, with a focus on biomass, which is any organic material with fuel capacities due to stored energy resulting from sunlight and which includes wood, agricultural crops and residues, food waste, and organic industrial waste.

Bioprocess engineering is a field that is related to biosystems engineering. It is concerned with the study and design of biotechnological processes that involve cell or enzyme catalysts causing chemical reactions. These processes are used in industry and agriculture to develop bio-based products or optimize production processes. They are used, among others, for producing food, feed, pharmaceuticals, chemicals, biofuels, and paper and for environmental engineering, including biological treatment of waste, water, and pollutants. Yogurt, beer, baking powder, ethanol, antibiotics, insecticides, detergents, and clean water are all products of bioprocess engineering.

Given the diversity of applications of biosystems and bioprocess engineering, the ethical issues associated with it are also diverse. Many of these issues concern health and environmental risks, for obvious reasons. Health risks are a potential issue whenever foods are chemically or biologically processed, and health and environmental risks occur when bioengineered agents end up in agricultural lands and water supplies. It certainly is not always clear beforehand whether bioengineered agents are safe and effective. It is well known, for example, that bioengineered pesticides have in the past caused great damage to ecosystems and have also been a source of health risks. Bioengineering has made industrial agriculture possible, which has had a deteriorating effect on the environment. At the same time, new developments in bioengineering could also support more sustainable forms of agriculture.

Other ethical issues are raised by the application of genetic engineering and synthetic biology in bioprocess, bioresource, and agricultural engineering. The introduction of genetically modified and newly designed cell and enzyme types has led to resistance to the use of genetically modified organisms (GMOs) in the agriculture and food industry, both for principled ethical reasons, and because of believed health and environmental risks. A final ethical issue concerns the development of biofuels as a sustainable energy resource (Thompson 2012). At first glance, it might seem that the development of biofuels would be a good choice in the transition toward more sustainable forms of energy. However, the development of biofuels requires the divestment of farmland to biofuel production, which decreases the food supply. This has led to a “food versus fuel” debate, in which opponents of biofuels argue that the emergence of a biofuel economy has increased global food prices, with detrimental consequences for poor people, especially in developing countries.

Biomimetics

Biomimetics, or biomimicry, is a rapidly expanding research field. It is concerned with the development of artificial devices, materials, systems, and processes that are modeled after aspects of biological systems. Biomimetics does not normally involve the use and engineering of biological cells, tissues, and systems. Rather, inspiration is sought in the structural and functional properties of biological systems for the development of nonbiological systems, materials, and processes. Properties that are mimicked may include functional properties of biological organs and systems like actuation, locomotion, and sensing; functional properties of biological tissues like adhesive, thermal, regenerative, and light-refracting properties; and structural properties of biological systems like the arrangement of leaves on a plant, the architecture of a human hand, and the design of a spider web. It also includes the mimicking of complex functional abilities of biological systems like the visual guiding and navigation behavior of honeybees and flock and herd behavior of animals.

Biomimetics finds applications in other engineering fields like robotics, artificial intelligence, and nanotechnology (which has yielded the field of nanobiomimetics) and in areas as diverse as environmental design, medicine, defense, aeronautics, and fashion design. Some examples of biomimetic materials, devices, and processes are:

- Velcro, created in 1955, based on the sticky, spiny seed chambers of the cocklebur
- Aircraft wing design and flight techniques inspired by birds and bats
- Stronger and lighter ceramics based on the architecture of sea shells
- Biomimetic artificial joints and muscles
- Buildings, such as the Eastgate Centre in Zimbabwe, that attain impressive thermal control by mimicking the heat transport properties of termite mounds
- Nanotechnologically engineered plastic surfaces with a microscopic texture that mimics shark skin and that impedes the growth of bacteria
- Self-healing polymer and polymer composite materials with a structural ability to repair damage caused by mechanical usage
- Artificial lipid bilayer membranes that mimic cell walls, including capabilities for self-assembly, chemical sensing, and sequencing DNA-molecules
- Biomimetic autonomous underwater vehicles that mimic the physiology and behavior of lobsters
- Microair vehicles (MAVs), which are small reconnaissance drones that mimic insect flight capabilities

Biomimetics has already led to significant achievement and brings many more promises for the future, for innovative materials, devices, and processes in a wide range of application domains. One particular promise is for sustainability. In sustainability contexts, biomimetics is often called biomimicry, a term that was coined by Janine Beynus (1997) in her seminal book *Biomimicry*: *Innovation Inspired by Nature*. Beynus' central claim is that a biomimetic approach to human development is necessary to make society sustainable. A biomimetic approach will emulate the circular economy of ecosystems in which waste is reused as a resource and in which technological design is congruent with nature. Her ideas have inspired much recent environmental thought and action.

Imitation of nature may enhance sustainability, but it may also come at a price. In the long term, biomimetics could undermine the observable difference between artificial and biological systems, because artificial systems start behaving and looking more and more like biological systems. This could lead to mistaken identities and a greater distrust of living nature: are the birds and insects that one sees in the skies or fish in the lake biological, or are they artifacts controlled by other humans? The introduction of self-assembly in biomimetic systems, particularly in self-assembling nanoscale systems, may in the long term introduce risks of technology gone rampant: self-repairing and self-replicating technology that cannot easily be controlled or stopped by humans.

Biomimetic robots and machines could also diminish autonomy, by functioning as autonomous agents that make choices for humans. Biomimetics could also introduce new forms of surveillance that threaten privacy, such as surveillance by microair vehicles and birdlike systems. Military applications of biomimetics could open up a new frontier in warfare. In particular, biomimetic robots that imitate humans and animals, like dogs, snakes, caterpillars, bees, and ants, could lead to a new wave of robotic warfare. In as far as such systems are autonomous and are used for lethal action, they raise ethical issues about the moral permissibility of using autonomous systems for killing. In addition, there is the question whether such systems can sufficiently discriminate between combat and noncombat situations and could escape the battlefield.

Conclusion

This entry reviewed ethical issues in bioengineering, including issues in biomedical engineering and its various subfields, in biosystems and bioprocess engineering, and in biomimetics. It was argued that because of the relative novelty of the field, there is currently no distinct academic field of bioengineering ethics and that ethical issues in bioengineering are currently studied in bioethics, medical ethics, and engineering ethics. The entry then proceeded with a review of ethical issues in biomedical engineering, including issues in cellular, genetic, and tissue engineering; biomaterials, prostheses, and implants; biomedical imaging and optics; and neural engineering. Ethical issues in these fields concern the rights and interests of patients, including autonomy, well-being, dignity, privacy, and acceptable risk, and the moral permissibility of using biological materials for novel purposes, modifying human genomes and reengineering the human body.

Next, biosystems and bioprocess engineering were reviewed, which are fields that focus on food, agricultural, pharmaceutical, and environmental applications, and ethical issues were identified in relation to health and environmental risks, the development of genetically modified organisms, and the effects of biofuel production on global food resources. Finally, biomimetics was discussed, including ethical issues that concern the blurring of the distinction between the natural and the artificial, risks in self-repairing and self-replicating technology, limitations to autonomous choices, and military applications.

We will conclude this entry by pointing to the fact that bioengineering is a young field with an astounding potential for new developments at the intersection of biology, medicine, and engineering. For this reason, it is to be expected that many new ethical issues will emerge in the coming years and decades. From the point of view of global health and global economic development, it may be especially important for the field to refocus some of its priorities to not only reflect concerns with Western health and agriculture but also with global issues in health, environment, and development. Bioengineering has the potential to greatly enhance global food security, water and environmental quality, and sustainable energy production, all of which are extremely important to global health, but achieving these developments would require the setting of new priorities in the field (Leduc et al., 2014).

Cross-References

- ▶ Agricultural Ethics
- ▶ Biotechnology
- ▶ Cybernetics
- ▶ Enhancement
- ▶ Food Ethics
- ▶ Genetic Modification: Animals/Food/Human Beings
- ▶ Neurotechnology
- ▶ Regenerative Medicine
- ▶ Synthetic Biology

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