Mind Over Matter

Building a Limitless Future Through Biodesign

William F. Holmes

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mccollum@3mpub.com

Dedication

To Leslie – my unfailing support

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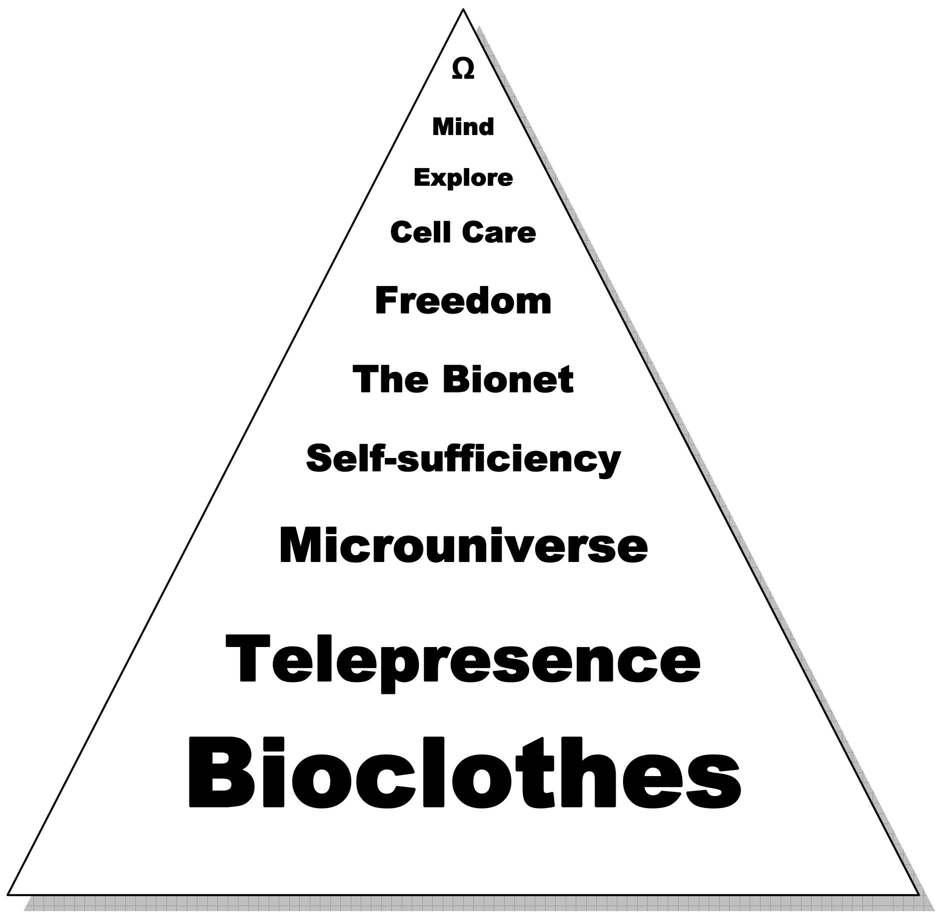
Prologue

Writing about the future is always an exercise in speculation, projecting trends from the past and present into the future. When and why does it matter? It matters when the trends point towards dramatic changes within a credible period of time, such as five to twenty years. Such trends need careful examination in order to guide our actions from the present onward, for decisions today will determine how we live tomorrow. The following pages examine the trend towards manufacturing devices of microscopic size. We are moving into a future where we can build structures of biological complexity. Technology and biology are gradually merging at the level we will call **biological design**. Human nature, which includes all the tangible objects we make and all the mental concepts we use to make them, will gradually intermingle with the rest of nature.



The above figure visualizes the major concepts in the order they are presented in the book, from bioclothes to exploring the mind, a series of steps leading towards a time beyond our powers of vision. However, life is never so neat. Even today, we are moving towards all these steps at once, although more rapidly towards the nearer ones.

The book reflects the author's belief in the destiny of the human mind, both as an individual and as a member of humanity. Collectively our minds form the mind of humanity, which moves through time from pre-history towards a future barely seen, then beyond to the as yet inconceivable. Humanity has created a complex technological world of material objects, whose use and very meaning are imbedded in the actions of our minds. Tools, clothing, houses, machines, factories, language, art, and music are all manifestations of our minds, with varying degrees of material form. The most distant steps in the figure represent our progression to a time when mental growth will predominate, when we will indeed become “mind over matter”.

1. A Quick Preview

The Trend to the Small

The ever-decreasing size of microcircuits is the paradigm for the trend to the small, producing ever more powerful microcomputers along with fast and portable communication systems to support the Internet. Less noticed are the decreasing size and cost of sensing devices for measuring sight, sound, touch, chemicals, microorganisms, mutations, and more. The massive proliferation of small video cameras for public surveillance is a dramatic example. We are gradually gaining the ability to put the entire world under the public eye.

Up to now computers and faster communications have not changed our lives dramatically. The changes have been incremental, a thousand improvements, many unnoticed. The sudden growth of the Internet has made the greatest impact, but for most of us the Internet is merely a set of useful services for sending messages, sharing ideas, playing games, instant ordering, and easy access to mountains of information. Our lives will change more dramatically when the trend to the small extends to mechanical devices as well, micro-motors, micro-switches, micro-pumps, micro-valves, and the like. Many of these micromechanical devices are still experimental, but some are already found in products for sale today. Their manufacture builds on the repertoire of methods used for making microcircuits. As the market for micromechanical parts increases, costs will drop and sizes grow smaller, following the same development path pioneered by microcircuits.

Microtechnology and Biodesign.

The marriage of these micro-machines with microcircuits will form a complete **microtechnology**. The assembly of large numbers of micro-size parts to make everyday articles such as clothes will create structures of biological complexity, gradually blurring the division between biology and mechanical technology. Designers will become **biodesigners**. Even now crude but useful wearable devices are being developed for communication, mechanical assistance, and projecting hand and arm motion to a distant site for remote operation. Robots are evolving from programmable machines into devices capable of human hand-eye manipulations.

The short and longer run benefits of microtechnology include a higher standard of living for everyone, with the potential for using fewer natural resources than today. Further along, there is the likelihood of independence from the job world through a high degree of local or even individual self-sufficiency based on small workshops and eventually micro-workshops. Finally, as the natural biotechnology of cells in the body and brain become thoroughly understood, individuals will largely direct their own health care. We will come to understand the operations of our minds well enough to maximize our mental health and expand our mental capacities.

Benefits and Risks

Along with the benefits will be the risks. Wide scale micro-manufacture will increase the possibility for surreptitious manufacture of destructive devices, both mechanical and biological. The need will always exist to keep watch over the activities of individuals and groups throughout the world, while guarding with equal care our political, economic, and biological independence from the endless pressures for maximum security. As we examine the potential of microtechnology, we shall refer again and again to two concepts:

1. Our basic human rights for political and economic independence, and the social obligations these rights imply.

2. The fundamental creative nature of the human mind, which must always remain free to explore.

2. Outline

The book is divided into an overview chapter followed by three parts with three chapters each.

1. "**Paths Into the Future**", introduces microtechnology and biological design, then describes succinctly their potential applications. Five basic challenges confronting society are posed, and how microtechnology will help meet each of them.

Part I, "**A World of Biostructures**", describes the great diversity of biodesigned structures external to the body. **Bioclothes** extend the concept of clothes to physical support, communication, recreation, health care, and instant transportation. Bioclothes plus **teleforms** will project our physical presence wherever communication paths reach, allowing us to work, shop, play, and travel while physically staying home. **Microteleforms** will open a vast new living space, the **microuniverse**. The earth's finite resources will no longer be a barrier to increasing prosperity for all.

Part II, "**Towards a Self-sufficient Society**", comes down to earth, covering jobs, the home workplace, robotics, and the potential for a high degree of self-sufficiency. The addition of sensing devices to our communication network will eventually create a kind of omnipresent **bionet** spreading throughout cities and countryside, watching and listening, sometimes acting. The bionet will become a system capable of detailed surveillance of all our public activities, while simultaneously bringing the power to travel by wire and radio wave wherever it reaches

Controlling the formation and use of omniscient data bases will be essential to maintaining a free society. Both the rights and the duties of citizens as individuals and members of society are examined - privacy, security, home production, public service, and trust. Above all, how can we ensure that our need for economic and political independence prevails over our fears?

Part III, "**Nurturing the Body, Mind, and Spirit**", looks inward to the body from the surface of the skin. It shows how we can gradually establish a personal **cell care**

network to maintain our health, guided in our designs by our body's existing care and reporting networks, the immune system and the nervous system. When we extend cell care networks into the brain, we will focus initially on repairing obvious defects from birth, accident, or disease. Later, as we come to understand how the brain functions in detail, we can enhance our minds by mental exercise and stimulated cell growth to optimize our mental health and skills. The final chapter will explore methods for discovering presently unknown mental powers by extending the neural structures of the brain well beyond the range of present human anatomy.

Signposts. At the end of each chapter (except the final one) there is a small list of items labeled "Signposts". Each item marks a significant step toward achieving the developments described in the chapter. Taken as a group, they are a set of signposts on the path to the future.

1. Paths Into the Future

"I was like a child by the sea ..." — Newton

1. Five Goals

Humanity has virtually remade the world, covering the earth with fields, farms, towns, and cities, fishing the oceans nearly bare, even altering the makeup of the atmosphere itself. As industrialism spreads from the developed world, our consumption of resources becomes ever larger, our mark on the earth ever greater. Is universal prosperity a mirage?

Fortunately a new path for development is emerging that leaves the earth less burdened, yet still fulfills our needs and desires. We can redirect our actions away from reconstructing the earth towards building a path into the sub-visible micro-world around us. Our planet shaping actions that overwhelm nature will give way to small, subtle, intricate designs that unobtrusively permeate nature, inspired by the structure of biological organisms. Our ever increasing demands on the earth's energy and material resources will reverse, diminishing towards the modest needs of our basic physiology. Our path into the micro-world will be guided by five basic goals that encapsulate our hopes and dreams for the future:

1. **Self-sufficiency.** How can individuals, families, and small groups provide for their basic material needs on their own property, freeing themselves from dependence on jobs that disappear by migration and automation?

2. **More Living Space.** How can we create enough resources and living space for universal prosperity without further degrading the earth?

3. **Personal Health Care.** How can we guide our personal health care to ensure a long, disease free life?

4. **Cultivating the Mind.** How can each of us guide our personal mental growth by learning how our brain and mind interact?

5. **Freedom and Security.** Our move into the world of the small is driven by our universal need for basic human freedoms, both physical and mental. As physical beings, we need the freedom to provide ourselves with food, clothing, shelter, health, and protection from bodily harm. As independent, rational beings, we demand the freedom to think, speak, and act, restrained only from actions that endanger others.

   How can we establish and maintain these universal freedoms, even in the face of malicious actions by individuals and groups, while retaining our independence from suffocating restrictions in the name of security?

2. The Principles of Biological Design

To achieve these goals, we must focus our creative energies on the micro-world that lies around and within us. Microtechnology and biotechnology will be our basic tools. Our inspiration will be the universe of biological organisms, where we find intricate structures from visible sizes all the way down to the fundamental molecules of DNA and proteins. Our micro-designs will become **biodesigns**, guided by four general principles:

Self-Sufficiency

All organisms are nearly self-sufficient. They need only a small number of raw materials and energy sources to maintain and reproduce all their molecular and cellular complexity. Green plants for example, need only sunlight, oxygen, carbon dioxide, water, and a few minerals. Animals need only a little more. Herbivores browse plants, grinding them up and digesting them into their biomolecular constituents, a small number of sugars, fats, amino acids (from proteins), nucleic acids (from DNA and RNA), vitamins, and minerals. These biomolecules serve as the raw material and energy sources for the animal to live, grow, and reproduce. Carnivores do the same, digesting their prey to the same basic molecules. Even the cells within an organism are nearly self-sufficient. A typical cell makes thousands of kinds of molecules, needing only a small number from outside for energy and materials. These amazing biological examples of nearly self-sufficient production on a very small scale establish a goal for the biodesigner: self-sufficient homesteads.

Cells

The world of living organisms contains a fantastic array of shapes and sizes, from flowers to alligators, from whales to bacteria. Yet magnifying our vision only a few hundred-fold reveals a constant pattern throughout the biological kingdom: every organism is built from cells. A small number of cell types combine by intricate arrangements to form the entire organism. The human body contains trillions of cells, but only a few hundred different types. We can further simplify by classifying cells into major categories.

The biodesigner will follow the example of biology, creating complex structures from large numbers of parts drawn from a small set of basic parts, most corresponding in function to a cell type (see Figure 1.1).

Small Size

Most cells are small, sub-visible specks to the unaided human vision, very roughly 10-20 microns across, less than the diameter of human hair. Muscle fibers and neuron axons resemble extremely fine hairs in width, but with lengths from the sub-visible to several feet. Our biologically motivated designs must use parts and devices similar in size to produce a full set of biological features. Only cell size devices can examine and repair our own cells without disrupting the tissues mechanically. Exploring our brain will require examining the simultaneous activities of many individual nerve cells without harm to the intricate neural networks. As our devices approach cell size, our designs will create an environment that blends with the natural world, which includes our own bodies, rather than fighting nature as we do today.

Sensory cells. Respond to touch, pressure, injury, sight, sound, smell, and more

Nerve cells (neurons). Receive, store, process, and transmit information

Muscle cells. Produce the body's motions, from heartbeats to speech to walking

Structural cells. Make bone, ligaments, tendons, and connective tissue

Barrier cells. Line the body's surfaces - the skin, gut, lungs, and blood vessels

Molecular factory cells. Transport, modify, manufacture, and secrete all the biomolecules distributed by the blood stream, from digested food to hormones

Energy storing cells. Primarily fat cells

Figure 1.1. Basic Cell Types in the Human Body

Behavior

The least understood area of biology is animal behavior. Roughly speaking, sensory and muscle cells are connected by an intricate network of nerve cells. While we understand far more today than a few years ago, much is still mysterious, especially the relationship of human behavior to the structure of human brains. In the absence of detailed knowledge, we can only imitate limited aspects of behavior by computer programs, such as recognizing a limited set of objects visually, or moving through a room without bumping into the furniture. Even the seemingly simple actions of insects are hard to duplicate. Nevertheless, useful "behaviors" are being achieved, especially for guiding robots. These behavior programs are primitive biodesigns, which will become more flexible with continuing design and increasing biological knowledge.

3. Microtechnology and Biodesigns

Before proceeding further, we will summarize in a few paragraphs the major concepts that form the substance of the book.

Microtechnology

Microtechnology is the art of building useful products from large numbers of microscopic parts. This multibillion dollar industry is already producing a variety of parts and devices of microscopic size. Until recently, microtechnology was largely restricted to electronic products, especially computer chips, which contain millions of simple electronic parts smaller than a typical cell. However the designer's toolbox is becoming far more versatile. A wide variety of microscopic parts are now available, including pumps, motors, switches, valves, movable mirrors, and sensors for light, heat, sound, force, pressure, and many chemicals. Some of these devices are so tiny that only a high-powered microscope can resolve all the details. The design and production of smaller, cheaper, and more versatile microparts will follow the same path as microelectronics.

Biodesign, Bioparts, Biostructures, and Bioclothes

Biological design is straightforward: combine a small number of cell types into the intricate structure of a biological organism. If we are guided by nature, our own designs will contain biological features that greatly extend their function, thus becoming **biodesigns**. We will call parts that emulate cells in size and function **bioparts**. Bioparts analogous in function to muscle, nerve, sensory, and structural cells will be assembled into **biostructures**. Clothes designers will be able to create garments that provide warmth or cooling, give physical protection and muscular support, recognize faces and voices, store vast quantities of information, and provide direct wireless connection to the whole world. Moreover such clothes can fit more perfectly than today's clothes, constantly adjusting in shape to conform to the movements of the wearer, while continually monitoring the body's respiration, heart activity, muscle tension, coordination, and basic metabolic activity. Such clothes will be **bioclothes**, a fundamental example of a biostructure. The concept of bioclothes easily extends to designing biostructures for furnishings and indeed entire dwellings. Our personal environment will adjust in size, shape, and function to our current needs, becoming a larger extension of our bioclothes, just as a tent is an extension of ordinary clothes.

Bioclothes as Teleforms

Bioclothes will also become the ultimate telephone, projecting sound, vision, touch, and physical actions through **teleforms**. The teleform will be an empty set of bioclothes adjustable in size and shape. When connected through the usual communication lines, a caller in bioclothes can effectively project his or her full physical being into the teleform, causing it to move as the caller moves, while receiving, sight, sound, and touch from the teleform. A person can work, visit, or play wherever there are teleforms, while physically staying at home.

The Microuniverse Around Us

If a teleform is much smaller than life size, then the environment in which it moves will seem correspondingly larger. A teleform one hundredth life size in height will move in an expanded microenvironment one million times larger in effective living space, a **microuniverse**. Although the familiar species of plants and animals will not scale down, there is a complex and fascinating microscopic flora and fauna, now barely visible, which will provide a new natural environment. Human built structures such as buildings can easily be reduced in size without loss of apparent detail. Even the most overcrowded city can provide its inhabitants with a few cubic feet for living in a psychologically spacious environment.

Seeing Everywhere - the Bionet

Surveillance is inevitable in the social and political climate of today's world, from street corner TV cameras and microphones to detectors for chemicals, germs, and nuclear radiation. A network of sensing devices will gradually spread throughout public buildings, factories, power plants, city streets, and the sky above them, eventually spreading to the highways and fields of the open countryside. The sensors will be connected to our already pervasive wired and wireless communication systems. As these sensing devices become steadily smaller and more numerous, they will gradually act like a gigantic, countrywide nervous system, watching and reporting on everything within its reach, A network of such unprecedented depth, breadth, and power for gathering information deserves its own name, the **bionet**. The government will inevitably collect information through the bionet. Individuals and private institutions will use the bionet for their own purposes. Everyone will want to know what others know about themselves. The rules for using the bionet will be crucial for the stability and trust that are fundamental to a livable society.

Cell Care Networks

The ultimate goal of human endeavor is truly to "know thyself". There is one path that clearly leads there, if we can follow it. We must literally explore our body and brain to understand the physical basis of our being. To send our senses into the body without mechanical disruption, our devices must be no larger than the wandering cells of the immune system that harmlessly move throughout the body. When a network of sensing bioparts is established, it will send a continuous stream of information from every part of our body to our bioclothes, which will condense and collate the flood of information into words, diagrams, and pictures at whatever detail desired. The bioparts forming this network may well be modified cells derived from the individual's body. Modified cells would make natural, personalized bioparts, free from immune reaction while sustaining themselves like normal cells from the metabolic resources of the blood and tissue fluids. Neurons and immune cells are both strong candidates for modification, since they already penetrate to every part of the body. Immune cells already have the capacity to modify their DNA, manufacturing antibodies to detect a single kind of molecule among millions of possibilities.

Ill health comes from damaged and malfunctioning tissues and organs, thus ultimately from malfunctioning or missing cells within them. Infectious bacteria are simply the extreme case; like cancer cells, their very presence is harmful. Cell care networks will eventually revolutionize medicine, by providing individual cell care. The sensing network can work in reverse, directly injecting healing or destructive substances into individual cells. Stem cells can be induced to divide when cell replacements are needed. The network's activities will be guided personally through the individual's bioclothes. The network need not handle the entire task of healing. It may simply "mark" cells with special biomolecules. Packets of substances released into the bloodstream would recognize the markers and release their contents into the cell.

Mind and Brain

The network will eventually penetrate into the brain, guided by its owner, monitoring simultaneously the activities of enormous numbers of neurons. By correlating neural activity or its lack with mental states, a picture of the mind will gradually emerge, showing the physical basis of our mental actions. Portions of the mind may be strengthened by careful mental exercises that stimulate the activity of specific neural networks, probably increasing the numbers and strengths of specific neuron projections and neurotransmitters. Some groups of neurons might be stimulated to increase their numbers by cell division. Each person will have the power to understand their particular strengths and weaknesses, adjusting them within an achievable range of mental capacity. The definitions of mental health will vary by individual and society, but the means to approach the ideals will become apparent.

The innate human drive to create and explore will not cease when we gain the power to ensure our mental and physical health. The brain itself will become an area to explore. New mental powers will be sought by investigating novel combinations of neural circuits, guided by our knowledge of existing circuits. Thus our eye sends signals for the primary colors of red, green, and blue from the retina to the brain, which combines them into the huge range of colors we perceive. If we add retinal neurons that detect a fourth primary color, and combine its signals with the other three, guided by knowledge of the brain's present color processing network, a greater, never perceived world of colors may arise. Almost any mental characteristic that one can associate with brain structure may extend into perceptions unimaginable today. None can know without trying.

Microtechnology and Nanotechnology

The manufacture of everyday products benefits enormously from human vision, as does microtechnology, which by definition spans a size range from roughly a millimeter to a micron. In biological terms microtechnology ranges from objects barely large enough for the fingers to handle down to objects the diameter of a typical bacterium. Fortunately this entire range of sizes can be seen with the standard light microscope. Every aspect of making, testing, and assembling microparts is fully open to human vision, just as in standard factory production. Thus biological design with parts even as small as cells will require no dramatic innovations, only the usual incremental advances we see in the design and manufacture of ordinary products.

Nanotechnology, by contrast works with sizes below the microtechnology range, from one micron (one thousand nanometers) down to atomic dimensions (tenths of nanometers). Vision in the nanotechnology range is much more limited, primarily electron microscopes operating in a high vacuum and atomic probe microscopes moving over surfaces like a probing finger. Our human watch-it-happen vision with light waves no longer functions in the nanotechnology range. Not surprisingly, nanotechnology is much less advanced than microtechnology. However, we can still move a very long ways towards the biodesigned future described above by using the well-developed and visually accessible methods of microtechnology.

The Cell and Biotechnology

From the engineer's view, every cell is actually a marvel of nanotechnology, an entire, nearly self-sufficient factory with thousands of different kinds of machines, completely automated. The complexity comes from combinations of the cell's DNA, proteins, and fatty acids. Sequences of the four DNA bases code for the linear structures of thousands of different kinds of proteins. These genes of DNA are more than plans. A messenger RNA copy of the gene is made as a scaffold to assemble its corresponding protein molecule, using a set of twenty amino acids as molecular parts. Proteins are the cell's machines, motors, transporters, detectors, controllers, and structural members. Fatty acids combine with proteins to form the external wall and internal chambers of the cell.

The cell is an example of biological design on a much smaller, molecular scale. The simple "bioparts" of nucleic acid and amino acid molecules are combined into a large number of genes and proteins of many types. Biotechnology uses these natural biological molecules as tools to understand the activities within cells well enough to make useful modifications (or to find them in nature). Extending health care to cell care will certainly require biotechnology, at the very least the knowledge and means to detect malfunctioning cells and remedy their defects.

4. Reaching the Goals

In brief, how will biodesign, microtechnology, and biotechnology help us reach the goals described above?

1. Self-sufficiency

The modern industrial economy brings us an abundance of the necessities - food, clothing, and shelter. Even a long, healthy life is becoming the norm as medical knowledge advances. Endless hours of exhausting work are disappearing as machines steadily take over the burden. But there is a cost. The industrial economy is based on a world wide system of production and trade of great complexity, sustained by a myriad of specialized activities called jobs. Each job holder becomes a servant of the system, servicing a tiny part of the whole. The fear of unemployment by job migration or automation is never far from our thoughts. We have lost the confidence of our self-sufficient hunter-gatherer ancestors.

Microtechnology can reverse this historical trend to large enterprises by returning step by step to the home as the center of production. The homeowner can assemble much of what he or she needs from a relatively small number of bioparts, perhaps bought at a biopart hardware store, much as the weaver buys various yarns to make rugs and garments. Consumer grade versions of factory assembly robots will assemble many kinds of everyday products from standard parts. Modified inkjet printers already assemble complex structures by depositing drops and powders in patterns and layers. Pick and place machines perform thousands of micro placements simultaneously. These and similar assembly methods can pave the way towards small scale, home based manufacturing, for both the householder's personal use and for economic gain. These new "cottage industries" will lead towards greater economic independence for the householder. Bit by bit micro-sizing and biological design will provide methods for manufacturing and assembling most of the household needs on the premises.

2. More Living Space

Competition for land and resources leads to increased costs, crowding, pollution, and general environmental degradation. A gloomy future is seen by many if present trends continue. Microtechnology and biotechnology cannot directly enlarge the earth. However they can lead to more efficient living styles that have the effect of increasing resources while actually reducing the burden on the earth. Bioclothes and biostructure homes will reduce the need for heating, cooling, and lighting. Teleforms will permit realistic travel for business and pleasure without the cost in fuel for transportation. Food production will still require large amounts of land and energy, however crops designed for maximum yield in the face of variable weather and insect attack will feed more people per acre. Intensive hand cultivation by robot helpers will further increase yields. Finally, microteleforms will give us access to the microuniverse, a psychological living space of enormous potential size.

3. Personal Health Care

The ultimate health care will come from a cell care network that lets individuals observe their body from the inside, make diagnoses, take corrective actions, and follow the consequences. Cell care networks will not only prevent and cure disease, but increasingly will become a means to modify an individual's biological self towards his or her personal ideal. Constructing these networks will require a mature microtechnology that can produce cell size micro-devices, and a mature biotechnology with a reliable set of methods based on a comprehensive knowledge of the molecular activity of cells.

We are already moving along the development path. Numerous devices can be inserted harmlessly within the body for applications as diverse as measuring glucose in the blood to examining the lining of the intestinal system for abnormal growths. Advances in microtechnology will steadily reduce the size of these devices. Cell size carriers are being developed to recognize specific types of cells and deliver the carrier's contents inside. Both diagnostic and treatment substances can be delivered. Research and development in biochemistry and biotechnology will steadily improve the specificity, versatility, and efficacy of these carriers.

4. Cultivating the Mind

We will never truly understand our actions, emotions, and beliefs until we learn how the human mind functions, relating brain structure and activity to the mental events we experience internally. In particular, each of us is different, and needs a private method to examine our particular brain in action. When we have established a personal cell care network within the brain, we can use this network to design and implement a path to grow towards our personal mental ideal. Traveling this path will entail the literal growth of brain cells, requiring time, patience, and much mental effort. As individuals, our place in society will no longer be limited by genetics and upbringing. We can overcome our limitations. As a species, a world of unknown mental powers will await our exploration.

5. Freedom and Security.

Microtechnology is today's technology and tomorrow's, with an enormous potential for relieving many of the limitations, frustrations, and fears of today's world, but raising problems of its own. When people have productive facilities within their homes to produce most of their needs, they will also have the potential to produce destructive weapons of many kinds. Inevitably, there will be the malicious few who will direct their powers towards destructive ends.

We will need to watch each other. From homeowners to countries, all of us will have to accept greatly increased surveillance of our activities in order to preserve a peaceful society. Since knowledge is power, it will be vital that all the members of society participate, in order to prevent potentially dangerous accumulation of secret knowledge in any government or private organization. All methods of collecting and storing information must be subject to oversight by public committees drawn from every part of society. Public disclosure should be the rule, secrecy limited in scope and duration. The same principles must extend to countries – intensive, open international surveillance.

No matter what potential dangers we may imagine, freedom should always come first. Our love of liberty should override our fears for loss of life and property. Independence is the birthright of every human being, and the freedom and daring to create and explore is a fundamental characteristic of humanity.

I. A World of Biostructures

2. Bioclothes and Their Extensions

“Small is Beautiful” — E. F. Schumacher

1. The Many Functions of Bioclothes

Clothes are one of humanity's oldest creations, the boundary between the body and the environment. Our fur, our original biological boundary, has become a remnant of hair with little capacity for protection or insulation. In most environments a human being would perish without clothing; thus clothes have become a true extension of the body. Bioclothes build on this concept of extension, providing clothes with new capabilities that merge smoothly with the body’s natural actions. Bioclothes are shape changing fabrics embedded with a network of sensors, actuators, and information processors. The innermost layer will conform smoothly to the skin, transferring information and action both inward and outward. The outer layers will generate force and stiffness to bear weight and to augment our movements. Bioclothes will be made from cell size microparts that we will call bioparts, since they will resemble their biological counterparts in function. Bioclothes will require a new kind of engineering design, creating flexible materials that conform closely to the shape and motions of the body.

Figure 2-1 lists the special features that can be designed into bioclothes. Like all clothing, bioclothes will come in many pieces, each suited to its purpose, combining to form a complete outfit for the occasion. They will extend our opportunities for living, while consuming no more energy than the human body requires for normal activity.

2. The Structure of Bioclothes

The Tactile Interface

Our tactile sensory cells lie within our skin. Skin and cells form the physical and sensory boundary between the internal world of the individual and the external world of the environment. Bioclothes will likewise function as a physical and sensory boundary between body and environment. Sensors within the clothes will detect the least movement by or against the body, transmitting this information as shape, force, and motion. Subtle tightening will probe the surface resilience of the body, conveying a measure of muscle and skin tension. Microactuators will generate surface textures and deep pressure on the skin, producing all the tactile sensations encountered in life, such as itching, vibration, wetness, touch, sharpness, and pressure. Built-in restraints will prevent the clothes from generating heavy or penetrating forces that could harm the body. These sensors and actuators will be woven into the biocloth fabric on the side lying next to the skin, fitting to the skin's surface without wrinkles or noticeable binding. The simplest bioclothes will resemble a body stocking.

Super Clothes

Protection

- Insulate from external cold and heat
- Cool and heat
- Keep out wind and water
- Protect against harmful substances in the air - pollen, poison gases, microorganisms
- Stiffen and expand to counteract heavy pressure, falls, and blows

Decoration

- Change colors and patterns
- Change visual and tactile textures
- Generate sounds to accompany posture and motion
- Release scents to reflect mood and actions
- Adjust shape and fit
- Adjust draping to conform to body posture and motion
- Present a better-looking face

Body Extensions

Assisted Physical Support

- Supply missing strength and stability
- Assist sitting, standing, and walking
- Assist hand and arm motion

Extended Physical Capacities

- Amplify motions
- Extend the legs in length and strength for high speed running
- Create fins and breathing extensions for fish-like swimming
- Extend arms and body for gliding and possibly flying
- Improve one's physical appearance and strength
- Sexual prophylaxis and enhancement
- Extend the expressive power of the face and voice

Extended Motor Skills

- Refine hand skills
- Increase speed and coordination
- Enhance the play of musical instruments
- Improve body language

Extended Powers for the Senses

- Increased visual and auditory acuity; infrared, microscopic, and telescopic vision
- Compensation for sensory disabilities
- Aids to recognition
- New modes of tactile imaging
- Aids to memory; personal databases
- Direct wireless communication

Personal Health Care

Skin Care

- Wash
- Remove wastes
- Apply ointments and powders
- Treat cuts, abrasions, and open sores

Health Tests

- Pulse and blood pressure
- Electric fields - heart (EKG), brain (EEG), and muscle (EMG)
- Internal sounds - heart and lungs
- Temperature, local warm spots, and inflammation
- Skin color, rashes, and growths
- Visual and auditory sensitivity
- Eye refraction, clarity, and pressure
- Muscle shape, force, and elasticity
- Sore spots and lumps
- Internal structure and function by ultrasonic probing
- Internal biochemistry from breath, urine, and sweat composition

Figure 2-1. Some Properties of Bioclothes

Force, Motion, and Shape

Thicker bioclothes can have outer portions that adapt to the wearer's movements by changing in shape, elasticity, and effective strength to support many of the features listed in Figure 2.1. Microactuators within the fabric will exert mechanical forces much like muscle cells, modifying the stresses throughout the fabric to create the desired degree of stiffness while exerting the necessary forces on the body and environment. The actuators will be embedded in a matrix of stiff and elastic elements of various shapes, giving the designer a wide range of options for changing the shape of the bioclothes as they respond.

It is unlikely that one design can serve all the functions listed in Figure 2-1, but a wide variety of bioclothes can be constructed from a small number of basic microparts. Figure 2-2 below is a representative list. The brackets [ ] show their rough biological counterparts.

Bioclothes Today

Human beings have worn simple versions of bioclothes for millennia. The first bioclothes were animal furs and leather, transformed by tanning and softening into warm, tough, flexible garments. Sewing probably followed, using animal fibers, plant fibers or strips of leather to piece together scraps of material to form almost any shape. Animal and plant fibers greatly expanded the possibilities for clothes, leading eventually to thread, yarn, weaving, and knitting. The cloth produced by these processes is constructed from fiber microparts twisted together into threads and yarns. Today's clothes incorporate a wide variety of natural and synthetic fibers, including elastic and metallic threads, which are woven, knitted, and sewn into many complex forms. They satisfy the first criteria for bioclothes, a flexible shape. However, most clothes are passive, responding by gravity to the general shape of the body. Elastic, body clinging clothes are more reactive, adapting themselves to the shape of the body. Anti-acceleration suits move a short step towards active force generating clothes by inflating air pouches to keep blood from moving from the brain and trunk into the legs. What is still missing? Complete bioclothes require at a minimum:

- A means to detect body shape
- Touch sensors
- Force generation

The computer animation industry has pioneered measuring the shape of the human body in motion, using bend sensors sewn into a body suit. The sensors respond to bending, producing data for calculating changes in body shape. A human actor goes through the motions of the character to be animated. The resulting set of data form a mathematical description of the changing body shape of the animated character going through the same motions.

Micropart/Biopart	Cell or Fiber
Mechanical - stiff and elastic	
Fibers, Struts, Rods	[bone, collagen, elastin]
Adjustable length	[muscle cells]
Sheets	[shell, cellulose, collagen]
Force, Motion	
Motors, Actuators	[muscle cells]
Contractile Fibers	[muscle cells]
Pumps	[muscle cells surrounding cavities]
Special Sensors	
Video camera	[rod and cone cells in retina]
Microphone	[hair cells of basilar membrane, inner ear]
Other Sensors	
Pressure, heat, chemical, etc.	[various sensory neurons]
Control	
Microcircuits	[neurons]
Communication Lines	
Wires and Optical Fiber	[neurons]
Transport	
Tubes, Pipelines	[arteries, veins, capillaries]
Power	
Batteries, Generators, Fuel Cells	[all cells]
Wires	[capillaries (carrying glucose for fuel)]

Figure 2.2 Microparts for Bioclothes

A number of groups over the years have sewn touch and bending sensors into ordinary gloves to form so-called data gloves. There are several commercial versions. Bend sensors produce information similar to the signals from the joint and tendon sensory nerves in the fingers and palm, allowing calculation of the conformation of the hand. Data gloves with bend sensors can capture fine details of hand movements for animations and medical studies. When a data glove also incorporates built-in force generation it becomes a true piece of bioclothes, a basic bioglove. A commercial version encases the fingers in kind of metallic exoskeleton visually comparable in size and looks to the bony skeleton of the fingers. The exoskeleton is powered through cables, exerting forces on the fingers. The microsized descendants of these gloves will have the capabilities we are seeking. There are several versions of exoskeletons for the legs and trunk in development. They are designed to let the wearer carry heavy loads of more than one hundred pounds for long periods. These developments can obviously help the disabled with limited leg strength to walk normally.

3. Protection

Ordinary clothes protect from heat, cold, wind, rain, and superficial injury. Tight weaves and water repellent fibers such as wool and nylon protect their wearer from wind and rain. Trapped air in the spaces between the fibers provides protection from cold, since immobile air is a good insulator. Protecting from heat is more complicated, since the clothes must block external heating by the sun while dissipating internal heat from the body. Light colored clothes with low thermal conductivity reduce the sun's power to heat by reflecting much of the sun's rays at their surface. The unreflected rays heat up the surface of the clothes, which primarily radiate the absorbed heat outward, since the insulating power of the material inhibits inward flow.

The excess heat produced by our body is removed by currents of cooling air (when it is cool), and more effectively by the evaporation of sweat. Air currents, cool or warm, accelerate the evaporation. Loose fitting garments automatically generate currents of air over the skin as the wearer moves, a design much favored by residents of hot climates.

Adjustable Insulation

Animal fur is more adjustable than clothing. Muscles in the hair follicles can raise and flatten individual hairs, changing the thickness of the trapped air, thus the degree of insulation. Goose pimples are the vestigial human response. Oil from skin glands forms a coating on the hairs, creating an effective barrier to water. Thus fur is a limited but effective prototype for bioclothes, with hair fibers and follicle muscles as biological microparts. Bioclothes will follow the same principles, functioning through the coordinated movement of its microparts. A typical set of clothes will combine insulation with rapid changes in shape, force, and stiffness. A system of fibers with flexible attachments, some stiff, some contractile, can trap air in the same manner as fur. Chambers with controlled openings would trap air even more effectively, while providing elastic mechanical support as well. The outer surface of the clothes will be covered with micro-shingles of waterproof material for cold, wind, and water protection, with adjustable openings to dissipate heat and water vapor. Layers of biological micro-shingles cover the surface of the human skin. They are formed by living cells that gradually move upward to the surface from the basal layer of the skin. As the cells rise, they flatten and fill with fibrous and lipid materials until they form layers of waterproof shingles.

Bioclothes might also regulate temperature by changing colors from bright to dark. Rapid color change is well known biologically. Pigment cells in the skin of cephalopods contain sacks of color that stretch flat to create microscopic color spots. The pigment cells of many fish contain colored granules that disperse rapidly throughout the cell to effectively color the entire cell with the granules. Bioclothes could emulate this biological design directly, or by covering and uncovering colored panels.

Heating and Cooling

Heating by a system of wires and electric heaters is straightforward. Cooling is more complicated. Liquid cooling requires a network of tubing and pumps to move liquid refrigerant close to the skin. Air-cooling implies a system of air passages. The larger problem is an energy source that is sufficiently light and compact to build into the clothes, yet will last many hours before renewal. Micro-size fuel cells or generators are the likely answer. Fortunately, bioclothes will be able to support their own weight, so that bulk is the greater concern. Nevertheless, energy efficiency will be a very high priority for all of the "active" features of bioclothes.

Pure Air

The atmosphere is full of potentially harmful viruses, bacteria, pollen, spores, dust, and chemicals from the natural environment, plus a host of manufactured chemicals and pollutants. All of these can be filtered from the air before we breathe it. Personal masks are the most effective, ensuring pure air at the point of inspiration. However today's masks are bulky and uncomfortable, worn primarily by workers exposed to atmospheres with high levels of harmful substances, plus a few people with seriously compromised immune systems. Bioclothes can actively pump air through the filter so that breathing requires no extra effort. The filter can be located away from the face, forming an integral part of the clothes. The pure air can be filtered, then pumped to the nose or mouth. The air passages would be embedded in an active face cover extending around the mouth and nose. The visual appearance and expressions of the face can remain about the same, the face covering being quite thin and reproducing the underlying facial shape and skin appearance on its surface (see **Decoration** below).

Nerve gases like Sarin and lethal microorganisms such as smallpox can enter the body through the skin. In emergencies, whether natural, accidental, or caused by terrorists, a fully impermeable body suit with built-in air conditioning for long term comfort can completely protect its user.

Physical Protection

All clothes provide some physical protection against abrasion, scratches, and bruises through the thickness and strength of their material. Helmets, shoulder pads, and the like protect against stronger blows, but become increasingly heavy and awkward as body coverage is extended. Bioclothes will respond adaptively by incorporating flexible fibers that stiffen when a force is exerted. A sensing network detects the strength and location of the force and directs the appropriate fibers to stiffen. Ordinary muscle responds the same way, stiffening against an applied force. Our eyes and ears also feed signals to a rapid warning system that generates muscle tension when danger is near. Bioclothes can detect potential collisions through sonic or electromagnetic measurements of distance and speed. The extra warning time will provide an opportunity for greater protection against heavy forces. A system based on air bag design could deploy as an instantaneous shock absorber.

Asbestos suits protect against heat and fire, while space suits block atmospheric air from leaking into the vacuum. Both are heavy and bulky, impeding the wearer's movements. Designing these suits with active systems will greatly improve their usefulness and comfort. Since they are full suits, they can transfer their own weight to whatever part of the suit surface bears the weight. Today's suits are awkward, since their stiffness and thickness make bending difficult and dulls the sense of touch. Active bending and compressing in response to body movements can make these suits much more usable. Active heating or cooling will compensate for the decreased insulation thickness arising from temporary compression.

Bioclothes will protect with minimal inconvenience and discomfort for the wearer. All things being equal, thicker clothes will give greater protection. The wearer can select light clothes to protect from everyday mishaps, and heavier ones for high-risk occupations and sports. Although clothes can be designed to protect against accidents from nature and peaceful human activities, they will never be a sure protection against malicious action. Even if we design a walking tank for personal protection, others will design weapons that penetrate.

4. Decoration

Clothes protect from cold, rain, sun, and prying eyes. But clothes have another purpose of equal importance. They determine how we present ourselves to the society in which we live. A glance around the world and back through time shows human beings as creatures of ever-changing appearance. Body decoration begins at the skin with paints, powders, perfumes, tattoos, and piercing ornaments. Head and facial hair are trimmed, anointed, and shaped. Fiber and fur of every shape, texture, and color form the clothes proper, complemented by rings, bracelets, anklets, garters, necklaces, headbands, and hats. Decoration serves many functions - status, membership, rank, intimidation, attraction, and beauty. The egalitarian beliefs of our society permit anyone to wear whatever is for sale. Visual interest and novelty have become the criteria of choice. Fashion rules.

Clothes that change their appearance on demand will foster even more visual independence, while avoiding the heavy costs of a large and changing wardrobe. Bioclothes can alter their surface to display images and designs of any color. Surface micro-shaping will vary the texture as well, appearing much like variations in fiber and weave. The clothes can become a camouflage suit, altering its appearance to blend into the visual environment, a common biological adaptation. Since bioclothes can change shape as well as surface appearance, they might assume the outer shape of a rock, a tree trunk, a piece of furniture, or indeed any shape that contains enough internal space for the wearer to stand, sit, crouch, or lie flat. Recent research even raises the possibility of “invisibility cloaks”, which guide light rays around the object within, emitting them on the other side in the same direction they were originally traveling. Even partial invisibility would greatly augment traditional camouflage.

Visual appearance can also respond to the movements of the wearer, or even change