SMART MATERIALS AND TECHNOLOGIES IN ARCHITECTURE

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List of Plates

Figure 1 Aerogel (http://www.geekologie.com/) .............................................................. 8

Figure 2 Monsanto’s ‘House of the Future’ (http://www.plasmacor.com/) ......................... 19

Figure 3 Human Nervous System (http://www.drdavidmartino.com/) .............................. 21

Figure 4 Human Brain (http://chattahbox.com/) ............................................................... 23

Figure 5 Change of form in Photochromic materials (http://4.bp.blogspot.com/) ............... 44

Figure 6 Change in colour in Thermochromic materials (http://bilbo.chomp.uri.edu/) ....... 45

Figure 7 Row-elwire (http://www.oneswitch.org.uk/) ......................................................... 55

Figure 8 Memory wire (http://talkingelectronics.com/) ..................................................... 60

Figure 9 Shape memory polymer (https://s3.amazonaws.com/) ......................................... 62

Figure 10 Photovoltaic (http://www.energy.ca.gov/) ........................................................ 65

Figure 11 Thermoelectric (http://www.nature.com/) ......................................................... 68

Figure 12 Piezoelectric (http://www.askoki.co.uk/) .......................................................... 75

Figure 13 Fiber optic section (http://talesofacoldadmin.files.wordpress.com/) ................. 81

Figure 14 The Smart Window system chart (http://physics.unc.edu/) ............................... 88

Figure 15 Emilio Pinero 2 (http://www.hoy.es/) .............................................................. 93

Figure 16 Emilio Pinero 1 (http://www.hoy.es/) .............................................................. 93

Figure 17 Kuwait Pavilion (http://www.lunactus.com/) .................................................... 94

Figure 18 Folding egg (http://www.tuvie.com/) .............................................................. 94

Figure 19 Heliotrope House (http://nano-cabin.com/) .................................................... 95

Figure 20 Interactive Facade (http://www.notcot.org/) ................................................... 96

Figure 21 Institute Du Monde Arabe (http://www.archnewsnow.com/) ......................... 97
Figure 22 Topotrnsegrity (http://vanguard.wordpress.com/) ................................................................. 98
Figure 23 Topotrnsegrity 2 (http://vanguard.wordpress.com/) .................................................................. 99
Figure 24 EnterActive (http://publicartinla.com/) ................................................................. 100
Figure 25 Bubbles interaction (http://www.interactivearchitecture.com/) .................................................. 101
Figure 26 The room Form (http://www.spatialrobots.com/) ................................................................. 102
Figure 27 The form (http://www.emeraldinsight.com/) ................................................................. 102
# Table of Contents

Acknowledgement .................................................................................................................. 1

List of Plates .......................................................................................................................... 2

CHAPTER 1: INTRODUCTION TO SMART MATERIALS ......................................................... 7

1.1 INTRODUCTION .................................................................................................................. 8

1.2 SMART MATERIALS ........................................................................................................... 10

1.3 SMART TECHNOLOGIES .................................................................................................. 14

1.4 NEED IDENTIFICATION .................................................................................................... 15

1.5 AIMS AND OBJECTIVES ................................................................................................... 16

1.5 SCOPE ............................................................................................................................... 16

1.6 LIMITATIONS .................................................................................................................... 17

1.7 RESEARCH METHODOLOGY .......................................................................................... 18

1.8 CASE STUDIES ................................................................................................................... 18

CHAPTER 2: HUMAN BODY AND THE BRAIN ....................................................................... 20

2.1 INTRODUCTION .................................................................................................................. 21

2.2 HUMAN BRAIN .................................................................................................................. 22

2.3 FUNCTION .......................................................................................................................... 24

   Intelligence, learning, and memory. ....................................................................................... 24

   Movement ............................................................................................................................... 25

   Basic body functions. .............................................................................................................. 25

   The senses. ............................................................................................................................. 26

CHAPTER 3: OPTIMUM HUMAN ENVIRONMENT ................................................................. 28

3.1 INTRODUCTION .................................................................................................................. 29

3.2 THE THERMAL ENVIRONMENT OF THE BODY ............................................................... 30

3.3 THE LUMINOUS ENVIRONMENT OF THE BODY ............................................................. 33

3.4 THE ACOUSTIC ENVIRONMENT OF THE HUMAN EAR ................................................... 35

CHAPTER 4: CLASSIFICATION OF SMART MATERIALS .................................................... 37

4.1 INTRODUCTION .................................................................................................................. 38

   Property change ................................................................................................................... 39

   Energy exchange .................................................................................................................. 39

   Reversibility/directionality ................................................................................................. 40
Size/location................................................................................................................................. 40

4.2 TYPE CHARACTERIZATIONS.................................................................................................. 41

4.3 TYPE 1 SMART MATERIALS – PROPERTY CHANGING .................................................... 41

4.3.1 CHROMICS OR ‘COLOR-CHANGING’ SMART MATERIALS ............................................. 41

4.3.2 PHASE-CHANGING MATERIALS .................................................................................... 47

4.3.3 CONDUCTING POLYMERS AND OTHER SMART CONDUCTORS......................... 48

4.3.4 RHEOLOGICAL PROPERTY-CHANGING MATERIALS ................................................. 50

4.3.5 LIQUID CRYSTAL TECHNOLOGIES ............................................................................ 51

4.3.6 SUSPENDED PARTICLE DISPLAYS ............................................................................... 51

4.4 TYPE 2 SMART MATERIALS – ENERGY EXCHANGING .................................................... 52

4.4.1 LIGHT-EMITTING MATERIALS...................................................................................... 53

4.4.2 BASIC SEMICONDUCTOR PHENOMENA...................................................................... 56

4.4.3 PHOTOVOLTAICS, LEDS, TRANSISTORS, THERMOELECTRICS.............................. 57

4.4.4 PIEZOELECTRIC EFFECTS AND MATERIALS ................................................................ 58

4.4.5 SHAPE MEMORY ALLOYS ......................................................................................... 60

4.4.6 SHAPE MEMORY POLYMERS ..................................................................................... 62

CHAPTER 5: ENERGY SYSTEMS ................................................................................................. 63

5.1 INTRODUCTION.................................................................................................................... 64

5.2 PHOTOVOLTAICS .............................................................................................................. 65

5.3 MICRO AND MESO ENERGY SYSTEMS ........................................................................... 68

CHAPTER 6: STRUCTURAL SYSTEMS ......................................................................................... 70

6.1 INTRODUCTION.................................................................................................................... 71

6.2 CONTROL OF STRUCTURAL VIBRATIONS ........................................................................ 73

Piezoelectrics ................................................................................................................................. 74

Electrorheological and magnetorheological materials .................................................................. 76

Other materials ............................................................................................................................ 77

6.3 CONTROL OF OTHER STRUCTURAL PHENOMENA ....................................................... 77

CHAPTER 7: LIGHTING SYSTEMS ............................................................................................. 79

7.1 INTRODUCTION.................................................................................................................... 80

7.2 FIBER-OPTIC SYSTEMS ...................................................................................................... 81

7.3 SOLID STATE....................................................................................................................... 83

CHAPTER 8: FAÇADE SYSTEMS ................................................................................................. 85
8.1 INTRODUCTION ......................................................................................................................... 86
8.2 THE SMART WINDOW .............................................................................................................. 87
CHAPTER 9: THE SMART BUILDING CONCEPT AND ITS IMPLICATION ...................................... 90
9.1 INTRODUCTION ....................................................................................................................... 91
9.2 CASE STUDIES ......................................................................................................................... 93
  9.2.1 EMILIO PINERO ................................................................................................................. 93
  9.2.2 KUWAIT PAVILION ............................................................................................................ 94
  9.2.3 FOLDING EGG .................................................................................................................... 94
  9.2.4 HELIOTROPE (HOUSE) ...................................................................................................... 95
  9.2.5 INTERACTIVE FAÇADE ...................................................................................................... 96
  9.2.6 INSTITUTE DU MONDE ARABE ......................................................................................... 97
  9.2.7 TOPOTRNSECURITY – NON – LINEAR RESPONSIVE ENVIRONMENTS ................................. 97
  9.2.8 ENTERACTIVE ................................................................................................................ 99
  9.2.9 BUBBLES ........................................................................................................................ 101
  9.2.10 META-MORPHIC ARCHITECTURE .................................................................................. 102
9.3 THE ENERGY SOURCES ......................................................................................................... 103
  9.3.1 THE HUMAN BODY AS AN ENERGY SOURCE ................................................................ 103
  9.3.2 THE NATURAL FACTORS AS ENERGY SOURCES ............................................................. 104
  9.3.3 THE INTERNAL AND EXTERNAL ENERGY OF THE BUILDING ....................................... 104
9.4 THE REGULATION CENTER – THE BRAIN OF THE BUILDING .............................................. 105
9.5 THE STRUCTURAL SYSTEM ................................................................................................... 106
9.6 THE CONCEPTUAL BUILDING .................................................................................................. 107
CHAPTER 10: ANALYSIS AND CONCLUSION ............................................................................. 110
10.1 ANALYSIS ........................................................................................................................... 111
  10.1.1 SMART MATERIAL VERSUS SMART TECHNOLOGY ......................................................... 113
  10.1.2 LIFE CYCLE COSTING OF SMART MATERIAL TECHNOLOGIES .................................. 114
  10.1.3 ARCHITECTURAL USE AND FUTURE POSSIBILITIES .................................................... 116
10.2 CONCLUSION ......................................................................................................................... 117
Bibliography .................................................................................................................................... 120
CHAPTER 1: INTRODUCTION TO SMART MATERIALS
1.1 INTRODUCTION
Smart materials are ‘highly engineered materials that respond intelligently to their environment’ and can understand a typical climate and respond accordingly. With the invention of Aerogel in 1931 these materials are widely used in various fields of scientific research. The materials like photo chromic glass, thermo chromic, thermo tropic thermo electric, piezo electric etc. are the examples of smart materials used nowadays. However, these materials are quite expensive to use and have limited sustainability. The future of smart materials depends on the invention of cheaper materials and the diversity in usage. The smart materials nonetheless are the future of world architecture but still the ideology of the usage is limited to a great extent.

The smart technologies are firstly used by Greeks and the ancient building techniques of every region contain some of these technologies which are neglected these days. The use of 400 mm thick wall and the construction of small openings in the hilly regions of Himalayas also come under these technologies.

The human body is like a building which has our bones as the structural members, the skin as the building facade and the inner organs together serving a living form called the brain. This brain interprets the outside world and gives the output in form of speech derived from
thoughts. The modern buildings lack a brain which can interpret the world outside and transform the ideas into a speech which can be understood by the others. We can learn from the human body and try to join the new technologies with the architectural imagination to form a new type of building system which can sustain every climate condition and have the capability of intelligently responding to the environment.

The vast majority of the built environment is completely static, opposite of the continuous alterations the natural environment endures. Parallel with nature, humans are constantly dynamic; moving, changing, sensing, and reacting to their surroundings and the information they process. These characteristics of humans and the buildings they occupy are utterly contrasting, thus creating a barrier between the two. This barricade is hindering the level of communication and response between both humans and the built environment. If this obstruction were to be eliminated, the built environment could adapt and react to humans and their needs which would amplify the experience of the space. Kinetic systems are implemented into architecture for this very reason; to create a level of interaction in conjunction with an interdependent relationship between humans and the spaces they inhabit.

**Research Question:** What are the Smart Materials and Technologies and what is the use of these materials in Architecture?
1.2 SMART MATERIALS
The relationship between architecture and materials had been fairly straightforward until the Industrial Revolution. Materials were chosen either pragmatically – for their utility and availability – or they were chosen formally – for their appearance and ornamental qualities. Locally available stone formed foundations and walls, and high-quality marbles often appeared as thin veneers covering the rough construction. Decisions about building and architecture determined the material choice.

The role of materials changed dramatically with the advent of the Industrial Revolution. Rather than depending on an intuitive and empirical understanding of material properties and performance, architects began to be confronted with engineered materials. Beginning in the 19th century with the widespread introduction of steel, leading to the emergence of long-span and high-rise building forms, materials transitioned from their pre-modern role of being subordinate to architectural needs into a means to expand functional performance and open up new formal responses. The industrialization of glass-making coupled with developments in environmental systems enabled the ‘international style’ in which a transparent architecture could be sited in any climate and in any context.

Indeed, the history of modern architecture can almost be viewed through the lens of the history of architectural materials.

The materials used nowadays for a sustainable design process are based on the resources available in the area. However when man is scientifically advancing at an exponential rate with
the use of technology, so why can’t the building in which he is living in should respond to the demands.

There are a number of types of smart material, some of which are already common. Some examples are as following:

- **Piezoelectric materials** are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied.

- **Shape memory alloys and shape memory polymers** are Thermo responsive materials where deformation can be induced and recovered through temperature changes.

- **Magnetic shape memory alloys** are materials that change their shape in response to a significant change in the magnetic field.

- **PH-sensitive polymers** are materials which swell/collapse when the pH of the surrounding media changes.

- **Temperature-responsive polymers** are materials which undergo changes upon temperature.

- **Halochromic materials** are commonly materials that change their colour as a result of changing acidity. One suggested application is for paints that can change colour to indicate corrosion in the metal underneath them.

- **Chromogenic systems** change colour in response to electrical, optical or thermal changes. These include electrochromic materials, which change their colour or opacity on the
application of a voltage (e.g. liquid crystal displays), thermochromic materials change in color depending on their temperature, and photochromic materials, which change colour in response to light - for example, light sensitive sunglasses that darken when exposed to bright sunlight.

- Non-Newtonian fluid is a liquid which changes its viscosity in response to an applied shear rate. In other words the liquid will change its viscosity in response to some sort of force or pressure. One good example of this is Oobleck, a fluid that seems to temporarily turn into a solid when a force is applied quickly. Another good example is Custard, as long as it is starch based. (Conrad, 1964)

- Ferrofluid

- Photomechanical Materials change shape under exposure to light.

- Self-healing materials have the intrinsic ability to repair damage due to normal usage, thus expanding the material's lifetime.

- "Smart" materials respond to environmental stimuli with particular changes in some variables. For that reason they are often also called responsive materials. Depending on changes in some external conditions, "smart" materials change either their properties (mechanical, electrical, appearance), their structure or composition, or their functions. (Flinn, 1986)

Mostly, "smart" materials are embedded in systems whose inherent properties can be favorably changed to meet performance needs.

- Colour changing materials
- Photochromic materials
Thermochromic materials

- Light emitting materials  Electroluminescent materials
- Fluorescent materials
- Phosphorescent materials

- Moving materials  Conducting polymers
- Dielectric elastomers
- Piezoelectric materials
- Polymer gels
- Shape memory alloys (SMA)

- Self assembling materials  Self assembling materials
- Self diagnostic materials  Optic fibres composite
- Smart composites
- Smart tagged composites

- Temperature changing materials  Thermoelectric materials
- Thickness changing fluids  Magneto-Rehological fluids (MRFs)

Smart materials are ideal for design because:

- Very reliable.
• Low power requirements (if used ideally).

• Can serve several functions at once (underlying principle in biomimetics).

• Fast-acting.

• Highly controllable.

1.3 SMART TECHNOLOGIES
The technological advance in the buildings is not based on the materials but is basically an enhancement of the inner environment and the look of the building facade. The embodied energy of a building and the humans living in it is mostly neglected. The basic system of a house is just the same as the human since Paleolithic age is used to the concept of a room with four walls and a roof to save it from the climatic factors, natural disasters and to provide it a certain level of privacy.

We humans have changed the way of living and we want a building to function as we want but are not providing it the right materials. It’s not hard to add the operational system of a system to that of a building and the buildings should be functionally aware of the changes around us. The materials should respond to a climatic change and external stimuli. The building should recycle ENERGY released by the human body during different processes and the energy of the change in environment due to the climatic factors.
1.4 NEED IDENTIFICATION

1. The building technologies are consuming a lot of energy which should be taken in account at a time when the world is going to face the energy crisis in the coming future.

2. The concept of a building is very old and it needs to be revised.

3. There are four seasons and every season have its different phases which are not taken into account when we are constructing a building.

4. The structural system should be revised to attain a limit of elasticity where the interiors can be changed according to the needs of the inhabitants.

5. The structural system should be strong enough to have a 0 risk factor of the earthquake.

6. The embodied energy should be taken into account while building in a large scale.

7. The ENERGY released from the human body during different conditions should be utilised.

8. The building should contain a BRAIN to act according to the inhabitant requirement.

9. The technological criteria for design need to revise.

10. The local material adaptation should be figured out with knowledge of the materials by the experts in the field of material scientology not by the adaptive feature of the human brain which takes knowledge from repetitive use consuming time.

11. The building should take energy from the climate change outside.

12. The SPACE derived from a FORM and the FORM of a building should have a common line for the energy usage, which should use recyclable energy.
1.5 AIMS AND OBJECTIVES

1. To understand the various technologies this can be used in day to day construction.

2. To list out the materials which are easily available for construction of Smart buildings.

3. To emphasise on energy conservation by usage of right technologies and materials.

4. To give a method for harnessing energy released by Human body and the process to recycle the energy.

5. To change the ideology that use of smart materials is expensive in comparison of locally available materials.

6. To conceptualize the BRAIN of a building and the functionality of it.

7. To revise the concept of exterior and interior energy and merge the energy systems.

8. To give a method for minimum power consumption by a building.

9. To create a common ground between the human body and the building.

1.5 SCOPE

1. The study shall cover the methodology for acquiring 0% exterior energy for inhabitant usage.

2. The study shall cover the concept of new building technologies which can respond according to the exterior climate.

3. The study shall cover the concept of new building technologies which can respond according to the interior necessity of the inhabitant.

4. The study shall cover the concept to merge the energy systems of a building.
5. The study shall cover the concept of technology which can be used to harness energy released by different environmental conditions and human body.

1.6 LIMITATIONS
1. The concept of the new system of building technology consists of the ideas of the author and the interpretation of the knowledge gained from various studies, which can be wrong in different criteria.

2. The time of study can also be a limiting factor as the area of research is vast and to answer the objective none of the steps can be skipped.

3. The main part of the study is based on the scientific research but the guidance is only limited to architectural expertise.

4. The characteristics of most of the materials can’t be judged because of the limitation of material labs in present time.

5. The case studies for such materials can only be done by Internet and none of the materials are tested in front of the author.

6. The practicality of the study can be questioned in terms of interpretation of the material behaviour.

7. The resources of the study are quite limited as the technology is quite new in the world Architecture and is practiced by very few authorities.
1.7 RESEARCH METHODOLOGY
1. The study will firstly focus on the energy materials which can sense temperature, light or any other kind of stimulus.
2. The following study will be derived from the scientific case studies on different materials and their characteristics.
3. The analysis of the case studies by NASA on the future materials.
4. The study of the living system and its derivations in technological world.

1.8 CASE STUDIES
THE HOME OF THE FUTURE
Keck and Keck took the inspiration of aircraft manufacturing a step further than their predecessors by including an aircraft hangar on the ground floor of their 1934 ‘House of Tomorrow’. The Aluminaire, built exclusively for the Museum of Modern Art’s first architectural exhibition in 1932, was intended as a demonstration of the potential of aluminum both as a facade material and for the structural system. Houses that demonstrated a company or industry’s latest material began to proliferate: the Masonite House, the Stran-Steel House, the Armco-Ferro Enamel House. As World War II was winding to a close, the US government supported an enormous enterprise that they hoped would solve two problems: the need for housing for the returning GIs, and a continuing market for the steel industry after the war. By the 1950s and 1960s, the home of the future was either a blatant marketing tool or a folly. Monsanto’s Home of the Future showcased many of the company’s plastic products as did General Electric’s Concept House. Coinciding with the shift from the industrial age to the information age, homes like Xanadu, with its amorphous polyurethane shell, marked the end of an era in which the material and the house were one and the same. Indeed, when Philips
Electronics unveiled their predictions for the Home of the Near Future in 1999, they described it as looking ‘more like the home of the past than the home of today.’ The intimacy between materials and architecture has always existed, but the 20th century represented a time when materials and technologies were given additional roles – ideological, didactic, and iconographic and the very pragmatic one of saving an industry. Materials continue to be chosen not so much for how they perform, but what they connote. As such, smart materials and new technologies pose a dilemma, because at the scale of their behavior, they have very few connotative qualities. (M., 1981)
CHAPTER 2: HUMAN BODY AND THE BRAIN


2.1 INTRODUCTION

If you think of the brain as a central computer that controls all bodily functions, then the nervous system is like a network that relays messages back and forth from the brain to different parts of the body. It does this via the spinal cord, which runs from the brain down through the back and contains threadlike nerves that branch out to every organ and body part.

When a message comes into the brain from anywhere in the body, the brain tells the body how to react. For example, if you accidentally touch a hot stove, the nerves in your skin shoot a message of pain to your brain. The brain then sends a message back telling the muscles in your hand to pull away. Luckily, this neurological relay race takes a lot less time than it just took to read about it.

Considering everything it does, the human brain is incredibly compact, weighing just 3 pounds. Its many folds and grooves, though, provide it with the additional surface area necessary for storing all of the body's important information.

The spinal cord, on the other hand, is a long bundle of nerve tissue about 18 inches long and ¾ inch thick. It extends from the lower part of the brain down through spine. Along the way, various nerves branch out to the entire body. These are called the peripheral

![Figure 3 Human Nervous System (http://www.drdaavidmartino.com)](image-url)
nervous system.

Both the brain and the spinal cord are protected by bone: the brain by the bones of the skull, and the spinal cord by a set of ring-shaped bones called vertebrae. They're both cushioned by layers of membranes called meninges as well as a special fluid called cerebrospinal fluid. This fluid helps protect the nerve tissue, keep it healthy, and remove waste products. Neurons send signals to other cells as electrochemical waves travelling along thin fibers called axons, which cause chemicals called neurotransmitters to be released at junctions called synapses. A cell that receives a synaptic signal may be excited, inhibited, or otherwise modulated. Sensory neurons are activated by physical stimuli impinging on them, and send signals that inform the central nervous system of the state of the body and the external environment. Motor neurons situated either in the central nervous system or in peripheral ganglia, connect the nervous system to muscles or other effector organs. Central neurons, which in vertebrates greatly outnumber the other types, make all of their input and output connections with other neurons. The interactions of all these types of neurons form neural circuits that generate an organism's perception of the world and determine its behavior. Along with neurons, the nervous system contains other specialized cells called glial cells (or simply glia), which provide structural and metabolic support. (Human Brain, 2000)

2.2 HUMAN BRAIN
The human brain is the center of the human nervous system and is a highly complex organ. Enclosed in the cranium, it has the same general structure as the brains of other mammals, but is over three times as large as the brain of a typical mammal with an equivalent body size. Most
of the expansion comes from the cerebral cortex, a convoluted layer of neural tissue that covers the surface of the forebrain. Especially expanded are the frontal lobes, which are involved in executive functions such as self-control, planning, reasoning, and abstract thought. The portion of the brain devoted to vision is also greatly enlarged in human beings.

The brain monitors and regulates the body's actions and reactions. It continuously receives sensory information, and rapidly analyzes this data and then responds, controlling bodily actions and functions. The brainstem controls breathing, heart rate, and other autonomic processes. The neocortex is the center of higher-order thinking, learning, and memory. The cerebellum is responsible for the body's balance, posture, and the coordination of movement.

In spite of the fact that it is protected by the thick bones of the skull, suspended in cerebrospinal fluid, and isolated from the bloodstream by the blood-brain barrier, the delicate nature of the human brain makes it susceptible to many types of damage and disease. The most common forms of physical damage are closed head injuries such as a blow to the head, a stroke, or poisoning by a wide variety of chemicals that can act as neurotoxins. Infection of the brain is rare because of the barriers that protect it, but is very serious when it occurs. (Human Brain, 2000)
2.3 FUNCTION
The basic functioning of the nervous system depends a lot on tiny cells called neurons. The brain has billions of them, and they have many specialized jobs. For example, sensory neurons take information from the eyes, ears, nose, tongue, and skin to the brain. Motor neurons carry messages away from the brain and back to the rest of the body.
All neurons, however, relay information to each other through a complex electrochemical process, making connections that affect the way we think, learn, move, and behave.

Intelligence, learning, and memory.
At birth, the nervous system contains all the neurons you will ever have, but many of them are not connected to each other. As you grow and learn, messages travel from one neuron to another over and over, creating connections, or pathways, in the brain. It's why driving seemed to take so much concentration when you first learned but now is second nature: The pathway became established.

In young children, the brain is highly adaptable; in fact, when one part of a young child's brain is injured, another part can often learn to take over some of the lost function. But as we age, the brain has to work harder to make new neural pathways, making it more difficult to master new tasks or change established behavior patterns. That's why many scientists believe it's important to keep challenging your brain to learn new things and make new connections— it helps keeps the brain active over the course of a lifetime. (Nervous system, 2000)

Memory is another complex function of the brain. The things we've done, learned, and seen are first processed in the cortex, and then, if we sense that this information is important enough to
remember permanently, it’s passed inward to other regions of the brain (such as the
hippocampus and amygdala) for long-term storage and retrieval. As these messages travel
through the brain, they too create pathways that serve as the basis of our memory.

**Movement.**
Different parts of the cerebrum are responsible for moving different body parts. The left side of
the brain controls the movements of the right side of the body, and the right side of the brain
controls the movements of the left side of the body. When you press the accelerator with your
right foot, for example, it’s the left side of your brain that sends the message allowing you to do
it.

**Basic body functions.**
A part of the peripheral nervous system called the autonomic nervous system is responsible for
controlling many of the body processes we almost never need to think about, like breathing,
digestion, sweating, and shivering. The autonomic nervous system has two parts: the
sympathetic and the parasympathetic nervous systems. The sympathetic nervous system
prepares the body for sudden stress, like if you see a robbery taking place. When something
frightening happens, the sympathetic nervous system makes the heart beat faster so that it
sends blood more quickly to the different body parts that might need it. It also causes the
adrenal glands at the top of the kidneys to release adrenaline, a hormone that helps give extra
power to the muscles for a quick getaway. This process is known as the body’s "fight or flight"
response. The parasympathetic nervous system does the exact opposite: It prepares the body
for rest. It also helps the digestive tract move along so our bodies can efficiently take in
nutrients from the food we eat.
The senses.
Your spouse may be a sight for sore eyes at the end of a long day — but without the brain, you wouldn't even recognize him or her. Pepperoni pizza sure is delicious — but without the brain, your taste buds wouldn't be able to tell if you were eating pizza or the box it came in.
None of your senses would be useful without the processing that occurs in the brain.
(Nervous system, 2000)

1. **Sight** - Sight probably tells us more about the world than any other sense. Light entering the eye forms an upside-down image on the retina. The retina transforms the light into nerve signals for the brain. The brain then turns the image right-side up and tells us what we are seeing.

2. **Hearing** - Every sound we hear is the result of sound waves entering our ears and causing our eardrums to vibrate. These vibrations are then transferred along the tiny bones of the middle ear and converted into nerve signals. The cortex then processes these signals, telling us what we are hearing.

3. **Taste** - The tongue contains small groups of sensory cells called taste buds that react to chemicals in foods. Taste buds react to sweet, sour, salty, and bitter. Messages are sent from the taste buds to the areas in the cortex responsible for processing taste.

- **Smell** - Olfactory cells in the mucous membranes lining each nostril react to chemicals we breathe in and send messages along specific nerves to the brain— which, according to experts, can distinguish between more than 10,000 different smells. With that kind of sensitivity, it's no wonder research suggests that smells are very closely linked to our memories.
4. **Touch** - The skin contains more than 4 million sensory receptors — mostly concentrated in the fingers, tongue, and lips — that gather information related to touch, pressure, temperature, and pain and send it to the brain for processing and reaction.
CHAPTER 3: OPTIMUM HUMAN ENVIRONMENT
3.1 INTRODUCTION
The ultimate task of architecture is to act in favor of man: to interpose itself between man and
the natural environment in which he finds himself, in such a way as to remove the gross
environmental load from his shoulders.  
- James Marston Fitch

The interior is characterized as a singular and stable environment
that can be optimized by maintaining ideal conditions. Indeed, one of the most prevalent
models of the ‘perfect’ interior environment is that of the space capsule. The exterior
environment is considered fully hostile, and only the creation of a separate and highly
controlled interior environment can complete this ideal container for man. This exaltation of
the space environment was the culmination of nearly a century of investigation into defining
the healthiest thermal conditions for the human body. In the 1920s, with the advent of
mechanical environmental systems, standards for interior environments began to be codified
for specific applications. School rooms were expected to be maintained at a constant
temperature and relative humidity, factories at another set of constant conditions. Over the
course of the 20th century, health concerns waned and the standards were tweaked for
comfort.

The design of enclosure is not the design of an environment. All environments are energy
stimulus fields that may produce heat exchange, the appearance of light, or the reception of
sound. Rather than characterizing the entire environment as being represented by a bulk
temperature, or a constant lux level of illuminance, we will define the environment only
through its energy transactions or exchanges across boundaries, including those of the human
body. This approach is consistent with the current understanding of the body’s sensory system.
Whether thermal, aural, or optical, our body’s senses respond not to state conditions – temperature, light level, etc. – but to the rate of change of energy across the boundary. For example, the sensation of cold does not represent an environment at a low temperature, rather it is an indication that the rate of change of thermal energy transfer between the environment and the body is increasing – the temperature of the environment may or may not be one of many possible contributors to this increase. (Conrad, 1964)

3.2 THE THERMAL ENVIRONMENT OF THE BODY
Our ultimate goal as designers is to provide for the health, welfare and pleasure of the human body. The human body does more than its share in maintaining its own health. An intricate and versatile thermoregulatory system can accommodate an astonishing range of environmental conditions – the peripheral skin temperature alone can vary from about 10 to 42 C without harmful consequences. The term homeostasis – the maintenance of a stable body temperature – is a bit of a misnomer, as it is only the temperature of the internal organs that must be maintained at a consistent level. The rest of the body functions as a heat exchanger, dynamically utilizing radiation, conduction, convection and evaporation to adjust the body’s thermal balance. A body in thermal equilibrium with its environment, defined as no difference between stable body conditions and stable surroundings, is not animate.

Thermal sensation is yet another differentiating aspect of the human nervous system, and, furthermore, it is not directly linked to the body’s thermoregulation as is commonly assumed. The cutaneous receptors (or what we traditionally call ‘touch’) respond to two large classes of
environmental stimuli – mechanical and electromagnetic energy. These receptors – known as mechanoreceptors and thermoreceptors – are excellent examples of boundary crossing in our thermodynamic system because they respond only to stimuli at the interface between our body and its surroundings. We recall, however, that there must be a difference in one of the state variables for energy to cross a boundary. As such, thermoreceptors do not sense ambient temperature at all, but rather they respond to the difference between our skin temperature and its surroundings. Skin temperature is one of the most variable of all of the body’s thermal regulation responses, and so we can assume that the difference is continuously shifting. Our lack of awareness of this constant adjustment of our thermal state is not due to the homogeneity of the surroundings; rather it is an indication that change is the normative state in the neurological system. The thermoreceptors do not produce a consciously aware sensation until the derivative of the change – the rate – begins to change. We might say that we only become aware of our surroundings when there is a ‘difference’ in the difference. The body is not a thermometer. The human body is the most typical of the heat exchanging entities within a building. If we characterize the building environment by the thermal phenomena commonly taking place, and not by the HVAC technology used to mitigate those phenomena, we will recognize that all of the phenomena result in buoyant behavior. Buoyancy occurs when gravity interacts with density. For example, we know that warm air rises and cool air sinks. Air density is inversely proportional to temperature, so as the temperature rises, the density drops. The action of gravity pulls the denser air toward the ground resulting in a vertical stratification of temperature from low to high as the elevation above the ground plane increases. The buoyant plume that surrounds the body is also found around other heat sources in the building –
lighting, computers, electrical equipment – as well as around many processes – cooking, heating, bathing. Any entity that produces heat within surroundings of air will exchange its heat through buoyancy. In addition, any time there is a difference in temperature between a surface entity and the surrounding air, there will be a buoyant boundary layer. The surface temperatures in a building, particularly those on exterior-facing components such as walls, windows, roofs and floors, are almost always different from the ambient air temperature, thus producing buoyant flow along surfaces. The interior thermal environment, rather than being a singular bounded state, is a large collection of buoyant behaviors, all of which have unique boundaries. (M. Clarke, 2001)

The HVAC system of today, and of the previous century, mixes and then dilutes these multiple energy systems for the purpose of controlling the temperature of the entire air volume. This is undoubtedly one of the least efficient ways of managing the human thermal balance. Compare this approach to another type of response to a common buoyant boundary layer problem – that of aerodynamic lift. Subtle and often microscopic modifications in the surface of an airfoil can dramatically affect the boundary layer conditions between the airplane wing and the atmosphere. If one treated this energy exchange problem in the same manner as we use for mitigating the energy exchanges in a building, then we would be trying to manage the pressure of the entire atmosphere rather than that within a few centimeters of the plane’s surface. In aerodynamics, the technology is developed and modified to respond to particular problems of physics. In building design, we modify the environment (the physical behavior) to optimize the performance of the technology. Action at the most strategic, and efficient level, requires knowledge of where the energy transactions naturally occur and an understanding of their
scale. HVAC systems are designed in relation to the scale of the building, whereas thermal behaviors operate at much smaller scales. The ideal response will occur at the boundary and scale of the behavior.

3.3 THE LUMINOUS ENVIRONMENT OF THE BODY
Just as our skin operates as the boundary between our body and the thermal environment, then so do our eyes with respect to the luminous environment. More specifically, that boundary is located near the back of our eye within the tiny region composed of our visual receptors – the rods and cones. Like any other surface, these receptors will selectively absorb certain wavelengths at certain energy levels. As children, many of us were taught about rods and cones, the rods serving for night vision and the cones for color. Wavelengths were attached to these, and we assumed that the cones were red, green and blue and that the rods saw only black and white. Advances in neurology and physical psychology during the past decade have given us a very different ‘view’ of the photoreceptors in the eye. The peak wavelengths for all of our receptors reside in the shorter to middle range of the visible spectrum – the three cones peak at 420, 530 and 560nm and the rods peak at 500 nm.

Essentially, our visible system is most sensitive to green. Current models of the eye separate its neurological response into two major categories: the ‘what’ system and the ‘where’ system which together replace the older rod/cone system. These two categories are associated with two different types of ganglion cells, with the larger cells producing the ‘where’ response and the smaller cells producing the ‘what’ response. The fundamental purpose of both types of
ganglion cells is to establish relative comparisons of photon reception between small areas of
the retina. Most of the comparisons take place through a center-surround receptor field – in
the center of the field photons excite the cell and in the surround of the field, photons inhibit
the field. As a result, a constant light level across the field produces a null signal, regardless of
how light or dark the level may be. Just as the body is not a thermometer, the eye is not a light
meter. Only when the receptor field encounters a difference in the photons across the area
does it signal the brain. In the ‘where’ system, these differences are responsible for the
perception of motion, depth and spatial organization, as well as the segregation of
figure/ground. The ‘where’ system is color blind, but is highly sensitive to differences in
luminance, or contrast. Conversely, the ‘what’ system is highly color selective, but is relatively
insensitive to luminance contrast. This system is responsible for object and face recognition,
and, of course, for color perception. Acuity is highest in the ‘what’ system, but the ‘where’
system is faster, making it ideal for perceiving motion. This new understanding of the visual
system has profound implications for designers and particularly for architects. If luminance
alone is responsible for the determination of where something is, then we have the possibility
of creating visual articulation of a surface where there is none, as well as vice versa. If color
alone is responsible for object recognition, then similar objects can be further differentiated by
a planned use of color. We will have the unprecedented ability to design how someone sees
and interprets information, as opposed to designing only what is placed in front of them.
(Livingstone, 2002)
3.4 THE ACOUSTIC ENVIRONMENT OF THE HUMAN EAR

Perhaps more has been known about the acoustic environment than any of the other two environments, but much less is known about how the ear responds than how the eye and the skin respond to stimuli. Only in the past 20 years have the roles of the two primary mechanoreceptors in the ear been identified, and their specific functionality is still being verified.

Unlike the eye, in which there is a one-to-one mapping of photons to photoreceptors, the mechanoreceptors must respond simultaneously to overlapping frequencies, amplitudes and directions of sound. Furthermore, whereas the eye has approximately 150 million receptors, the ear must perform its more complex role with only 20 000 receptors. Although there is universal agreement that the hair cells are the key to understanding the sensitivity of the ear, there is as yet no coherent theory on just how they work. The characteristic that we are most interested in as designers is how the ear spatializes sound. A large amount of our awareness of the space surrounding us comes from non-visual stimuli. Proprioceptors in our lower body give us a sense of how close or far from a wall we might be, while the mechanoreceptors in the ear give us the cue as to how spacious a room is. Just as the Ganzfeld effect, by eliminating luminance contrast, erases any visual comprehension of the dimensions of a space, so too does an anechoic chamber in regard to sound. Without a sonic feedback from our surroundings we are incapable of placing ourselves spatially in a room even if its walls are clearly defined visually. Many installation artists are beginning to experiment with sonic manipulation, creating spaces where there were none, and directing the localization of sound at will. Smart materials, in the form of piezoelectrics, are already playing the central role in sound design, but the
potential of designing the acoustic environment, as well as the thermal and luminous environments, directly may well be the most provocative application of smart materials in the design field. (Livingstone, 2002)
CHAPTER 4: CLASSIFICATION OF SMART MATERIALS
4.1 INTRODUCTION
This chapter first identifies characteristics that distinguish smart materials from other materials, and then systematically reviews many of the more widely used ones. We begin by noting that the five fundamental characteristics that were defined as distinguishing a smart material from the more traditional materials used in architecture were transiency, selectivity, immediacy, self-actuation and directness. If we apply these characteristics to the organization of these materials then we can group them into:

1. Property change capability
2. Energy exchange capability
3. Discrete size /location
4. Reversibility

These features can potentially be exploited to either optimize a material property to better match transient input conditions or to optimize certain behaviors to maintain steady state conditions in the environment.

The physical characteristics of smart materials are determined by these energy fields and the mechanism through which this energy input to a material is converted. If the mechanism affects the internal energy of the material by altering either the material’s molecular structure or microstructure then the input results in a property change of the material. If the mechanism changes the energy state of the material composition, but does not alter the material, then the input results in an exchange of energy from one form to another. A simple way of
differentiating between the two mechanisms is that for property change type, the material absorbs the input energy and undergoes a change, whereas for the energy exchange type, the material stays the same but the energy undergoes a change. We consider both of these mechanisms to operate at the micro-scale, as none will affect anything larger than the molecule, and furthermore, many of the energy exchanges take place at the atomic level. As such, we cannot ‘see’ this physical behavior at the scale at which it occurs. (D. M. Addington, 2005)

**Property change**
The class of smart materials with the greatest number of potential applications to the field of architecture is the property-changing class. These materials undergo a change in a property or properties – chemical, thermal, mechanical, magnetic, optical or electrical – in response to a change in the conditions of the environment of the material. The conditions of the environment may be ambient or may be produced via a direct energy input. Included in this class are all color changing materials, such as thermochromics, electrochromics, photochromics, etc., in which the intrinsic surface or molecular spectral absorptivity of visible electromagnetic radiation is modified through an environmental change (incident solar radiation, surface temperature) or a direct energy input to the material (current, voltage).

**Energy exchange**
The next class of materials that is expected to have large penetration into the field of architecture is the energy exchanging class. These materials, which can also be called ‘First Law’ materials, change an input energy into another form to produce an output energy in accordance with the First Law of Thermodynamics. Although the energy conversion efficiency
for smart materials such as photovoltaics and thermoelectrics is typically much less than for more conventional technologies, the potential utility of the energy is much greater. For example, the direct relationship between input energy and output energy renders many of the energy-exchanging smart materials, including piezoelectrics, pyroelectrics and photovoltaics, as excellent environmental sensors. The form of the output energy can further add direct actuation capabilities such as those currently demonstrated by electrostrictives, chemoluminescents and conducting polymers.

**Reversibility/directionality**
Many of the materials in the two above classes also exhibit the characteristic either of reversibility or of bi-directionality. Several of the electricity converting materials can reverse their input and output energy forms. For example, some piezoelectric materials can produce a current with an applied strain or can deform with an applied current. Materials with bi-directional property change or energy exchange behaviors can often allow further exploitation of their transient change rather than only of the input and output energies and/or properties. The energy absorption characteristics of phase changing materials can be used either to stabilize an environment or to release energy to the environment depending on in which direction the phase change is taking place. The bi-directional nature of shape memory alloys can be exploited to produce multiple or switchable outputs, allowing the material to replace components comprised of many parts.

**Size/location**
Regardless of the class of smart material, one of the most fundamental characteristics that differentiate them from traditional materials is the discrete size and direct action of the
material. The elimination or reduction in secondary transduction networks, additional components, and, in some cases, even packaging and power connections allows the minimization in size of the active part of the material. A component or element composed of a smart material will not only be much smaller than a similar construction using more traditional materials but will also require less infrastructural support. The resulting component can then be deployed in the most efficacious location. The smaller size coupled with the directness of the property change or energy exchange renders these materials to be particularly effective as sensors: they are less likely to interfere with the environment that they are measuring, and they are less likely to require calibration adjustments.

4.2 TYPE CHARACTERIZATIONS
For this discussion, we will distinguish between these two primary classes of smart materials discussed above by calling them Type 1 and Type 2 materials:

* Type 1 – a material that changes one of its properties (chemical, mechanical, optical, electrical, magnetic or thermal) in response to a change in the conditions of its environment and does so without the need of external control.

* Type 2 – a material or device that transforms energy from one form to another to affect a desired final state.

4.3 TYPE 1 SMART MATERIALS – PROPERTY CHANGING

4.3.1 CHROMICS OR ‘COLOR-CHANGING’ SMART MATERIALS

Fundamental characteristics of chromics
A class of smart materials that are invariably fascinating to any designer is the so-called ‘color-changing’ material group which includes the following:
* Photochromics – materials that change color when exposed to light

* Thermochromics – materials that change color due to temperature changes.

* Mechanochromics – materials that change color due to imposed stresses and/or deformations.

* Chemochromics – materials that change color when exposed to specific chemical environments.

* Electrochromics – materials that change color when a voltage is applied. Related technologies include liquid crystals and suspended particle devices that change color or transparencies when electrically activated.

These constitute a class of materials in which a change in an external energy source produces a property change in the optical properties of a material – its absorptance, reflectance, or scattering. So-called ‘color-changing’ materials thus do not really change color. They change their optical properties under different external stimuli (e.g., heat, light or a chemical environment), which we often perceive as a color change. Our perception of color depends on both external factors (light and the nature of the human eye) and internal factors such as those noted above. An understanding of these materials is thus more complicated than simply saying that they ‘change colors’.

The external factors that affect our perception of color are many. Color is fundamentally a property of light. All incident light can be characterized by its spectral distribution of electromagnetic wavelengths. Surfaces can only reflect, absorb or transmit the available
wavelengths – as such they are always subtractive. The human eye is also a subtractive surface, but does so comparatively. As a result, depending on the spectral and intensity distributions within the field of view, color is also relative within the context of the human eye. Of direct interest herein is that the observed color of an object also depends on the intrinsic optical qualities of a material. Since light consists fundamentally of energy impulses, it reacts with the negatively charged electrons in a material. Depending on the crystalline or molecular structure of the material, the light that attempts to pass through may be delayed, redirected, absorbed or converted to some other type of energy. The precise crystalline or molecular structure of the material present will determine which of these possible behaviors will take place, and in turn determine what wavelengths of light are in some way altered (which in turn affects the perceived color of the material). Interestingly, it is the molecular structure first encountered on a material’s surface that determines the resultant behavior. As such, thin films, coatings and paints will predominantly determine the response to light, more so than the substrate. In the case of a smart material with apparent color changing properties, the intrinsic optical properties – absorptance, reflectance, scattering – of the material are designed to change with the input of external energy. Fundamentally, the input energy produces an altered molecular structure or orientation on the surface of the material on which light is incident. The structure depends on chemical composition as well as organization of the crystal or the molecule. This external energy can be in several forms (e.g., heat or radiant energy associated with light), but in each case it induces some change in the internal surface structures of the material by reacting with the negatively charged electrons present. These changes in turn affect the material’s absorptance or reflectance characteristics and hence its perceived color. These
changes can be over the entire spectrum or be spectrally selective. Interestingly, these changes are reversible. When the external energy stimulus disappears, an altered structure reverts back to its original state. The main classes of color-changing smart materials are described by the nature of the input energy that causes the property change, and include photochromics, electrochromics, thermochromics, mechanochromics, and chemochromics. (Addington, 2004)

**Photochromic materials**

Photochromic materials absorb radiant energy which causes a reversible change of a single chemical species between two different energy states, both of which have different absorption spectra. Photochromic materials absorb electromagnetic energy in the ultraviolet region to produce an intrinsic property change. Depending on the incident energy, the material switches between the reflectively and abortively selective parts of the visible spectrum. The molecule used for photochromic dyes appears colorless in its inactivated form. When exposed to photons of a particular wavelength, the molecular structure is altered into an excited state, and thus it begins to reflect at longer wavelengths in the visible spectrum. On removal of the ultraviolet (UV) source, the molecule will revert to its original state. A typical photochromic film, for example, can be essentially transparent and colorless until it is exposed to sunlight, when the film begins selectively to reflect or transmit certain wavelengths (such as a transparent blue). Its intensity depends upon the directness of exposure. It reverts to its original colorless state in the dark when there is no sunlight.

![Figure 5 Change of form in Photochromic materials](http://4.bp.blogspot.com/)
Photochromic materials are used in a wide range of applications. Certainly we see them used in a wide range of consumer products, such as sunglasses that change their color. In architecture, they have been used in various window or facade treatments, albeit with varying amounts of success, to control solar gain and reduce glare. By and large, these applications have not proven effective because of the slowness of response and heat gain problems. (J., 1992)

**Thermochromic materials**

Thermochromic materials absorb heat, which leads to a thermally induced chemical reaction or phase transformation. They have properties that undergo reversible changes when the surrounding temperature is changed.

Thermochromic materials come in many forms, including liquid crystal forms used in thermochromic films and the leucodyes used in many other applications. Films are used in applications such as battery testers, thermometers and so forth. The widely used ‘band thermometer’ that is placed on a person’s forehead, for example, is made of thermochromic materials designed to be sensitive to particular temperature levels. A simple visual calibration device signifies the temperature level corresponding to a particular color. They can be precisely calibrated. Leucodyes, by contrast, are used in various paints and papers.
**Mechanochromic and chemochromic materials**
Mechanochromics have altered optical properties when the material is subjected to stresses and deformations associated with external forces. Many polymers have been designed to exhibit these kinds of properties. The old household device for imprinting raised text onto plastic strips utilizes a plastic of this type. The raised text that results from a mechanical deformation shows through as a different color. Chemochromics include a wide range of materials whose properties are sensitive to different chemical environments.

**Electrochromic materials**
Electrochromism is broadly defined as a reversible color change of a material caused by application of an electric current or potential. An electrochromic window, for example, darkens or lightens electronically. A small voltage causes the glazing material to darken, and reversing the voltage causes it to lighten.

There are three main classes of materials that change color when electrically activated: electrochromics, liquid crystals and suspended particles. These technologies are not one constituent materials, but consist of multi-layer assemblies of different materials working together.

Fundamentally, color change in an electrochromic material results from a chemically induced molecular change at the surface of the material through oxidation-reduction. In order to achieve this result, layers of different materials serving different ends are used. Briefly, hydrogen or lithium ions are transported from an ion storage layer through an ion conducting layer, and injected into an electrochromic layer. In glass assemblies, the electrochromic layer is often tungsten oxide (WO3). Applying a voltage drives the hydrogen or lithium ions from the
storage layer through the conducting layer, and into the electrochromic layer, thus changing
the optical properties of the electrochromic layer and causing it to absorb certain visible light
wavelengths. In this case, the glass darkens. Reversing the voltage drives ions out of the
electrochromic layer in the opposite direction (through the conducting layer into the storage
layer), thus causing the glass to lighten. The process is relatively slow and requires a constant
current. (Gandhi, 1992)

4.3.2 PHASE-CHANGING MATERIALS
Many materials can exist in several different physical states – gas, liquid or solid – that are
known as phases. A change in the temperature or pressure on a material can cause it to change
from one state to another, thereby undergoing what is termed a ‘phase change’. Phase change
processes invariably involve the absorbing, storing or releasing of large amounts of energy in
the form of latent heat. A phase change from a solid to a liquid, or liquid to a gas, and vice
versa, occurs at precise temperatures. Thus, where energy is absorbed or released can be
predicted based on the composition of the material. Phase-changing materials deliberately seek
to take advantage of these absorption/release actions.

While most materials undergo phase changes, there are several particular compositions, such
as inorganic hydrated salts, that absorb and release large amounts of heat energy. As the
material changes from a solid to a liquid state, and then subsequently to a gaseous state, large
amounts of energy must be absorbed. When the material reverts from a gaseous to a liquid
state, and then to a solid state, large amounts of energy will be released. These processes are
reversible and phase-changing materials can undergo an unlimited number of cycles without
degradation.
Since phase-changing materials can be designed to absorb or release energy at predictable temperatures, they have naturally been explored for use in architecture as a way of helping deal with the thermal environment in a building. One early application was the development of so-called ‘phase change wallboard’ which relied on different embedded materials to impart phase change capabilities. Salt hydrates, paraffins and fatty acids were commonly used. The paraffin and fatty acids were incorporated into the wallboard initially by direct immersion. Subsequently, filled plastic pellets were used. Transition temperatures were designed to be around 65–72 8°F for heating dominated climates with primary heating needs and 72–79 F for climates with primary cooling needs. (Alloys and Materials, 2002)

Products based on direct immersion technologies never worked well and proved to have problems of their own that were associated with the more or less exposed paraffin and fatty acids (including problems with animals eating the wallboard products). Technologies based on sealing phasechanging materials into small pellets worked better. Pellet technologies have achieved widespread use, for example, in connection with radiant floor heating systems. In many climates, radiant floor systems installed in concrete slabs can provide quite comfortable heating, but are subjected to undesired cycling and temperature swings because of the need to keep the temperature of the slab at the desired level, which typically requires a high initial temperature. Embedding phase-changing materials in the form of encased pellets can help level out these undesirable temperature swings.

4.3.3 CONDUCTING POLYMERS AND OTHER SMART CONDUCTORS
In this day and age of electronic devices, it is no wonder that a lot of attention has been paid to materials that conduct electricity. Any reader of scientific news has heard about the strong
interest in materials such as superconductors that offer little or no resistance to the flow of electricity. We will look at a broader range of conducting materials, including those that offer great potential in different design applications. In general, there is a broad spectrum associated with electrical conductivity through terms like ‘insulators’, ‘conductors’, ‘semi-conductors’ and ‘super-conductors’ – with insulators being the least conductive of all materials. Many of the products that architectural and industrial designers are most familiar with are simple conductors. Obviously, many metals are inherently electrically conductive due to their atomic bonding structures with their loosely bound electrons allowing easy electron flow through the material. Many traditional products that are not intrinsically conductive, e.g., glasses or many polymers, can be made so by various means. Polymers can be made conductive by the direct addition of conductive materials (e.g., graphite, metal oxide particles) into the material.

Glasses, normally highly insulating, can be made conductive and still be transparent via thin film metal deposition processes on their surfaces. There are other polymers whose electrical conductivity is intrinsic. Electroactive polymers change their electrical conductivity in response to a change in the strength of an electrical field applied to the material. A molecular rearrangement occurs, which aligns molecules in a particular way and frees electrons to serve as electricity conductors. Examples include polyaniline and polypyrrole. These are normally conjugated polymers based on organic compounds that have internal structures in which electrons can move more freely. Some polymers exhibit semiconductor behavior and can be light-emitting. Electrochemical polymers exhibit a change in response to the strength of the chemical environment present. A number of applications have been proposed for conducting polymers. Artificial muscles have been developed using polypyrrole and polyaniline films. These
films are laminated around an ion-conducting film to form a sandwich construction. When subjected to a current, a transfer of ions occurs. The current flow tends to reduce one side and oxidize the other. One side expands and the other contracts. Since the films are separated, bending occurs. This bending can then be utilized to create mechanical forces and actions. (Flinn, 1986)

4.3.4 RHEOLOGICAL PROPERTY-CHANGING MATERIALS
The term ‘rheological’ generally refers to the properties of flowing matter, notably fluids and viscous materials. While not among the more obvious materials that the typical designer would seek to use, there are many interesting properties, in particular viscosity, that might well be worth exploring. Many of these materials are termed ‘field-dependent’. Specifically, they change their properties in response to electric or magnetic fields. Most of these fluids are so-called ‘structured fluids’ with colloidal dispersions that change phase when subjected to an electric or magnetic field. Accompanying the phase change is a change in the properties of the fluid. Electrorheological (ER) fluids are particularly interesting. When an external electric field is applied to an electrorheological fluid, the viscosity of the fluid increases remarkably. (Smart Materials, 2003)

When the electric field is removed, the viscosity of the fluid reverts to its original state. Magnetorheological fluids behave similarly in response to a magnetic field. The changes in viscosity when electrorheological or magnetorheological fluids are exposed to electric or magnetic fields, respectively, can be startling. A liquid is seemingly transformed into a solid, and back again to a liquid as the field is turned off and on. These phenomena are beginning to be utilized in a number of products. An electrorheological fluid embedded in an automobile tire,
for example, can cause the stiffness of the tire to change upon demand; thus making it possible
to ‘tune’ tires for better cornering or more comfortable straight riding. Some devices that
typically require mechanical interfaces, e.g., clutches, might conceivably use smart rheological
fluids as replacements for mechanical parts. In architecture and industrial design, little use has
been made of smart rheological fluids. One can imagine, however, chairs with smart rheological
fluids embedded in seats and arms so that the relative hardness or softness of the seat could be
electrically adjusted. The same is obviously true for beds. (Smart materials, 2006)

4.3.5 LIQUID CRYSTAL TECHNOLOGIES
Liquid crystal displays are now ubiquitously used in a host of products. It would be hard to find
someone in today’s modern society that has not seen or used one. This widespread usage,
however, does not mean that liquid crystal technologies are unsophisticated. Quite the
contrary; they are a great success story in technological progress. Liquid crystals are an
intermediate phase between crystalline solids and isotropic liquids. They are orientationally
ordered liquids with anisotropic properties that are sensitive to electrical fields, and therefore
are particularly applicable for optical displays. Liquid crystal displays utilize two sheets of
polarizing material with a liquid crystal solution between them. An electric current passed
through the liquid causes the crystals to align so that light cannot pass through them. Each
crystal is like a shutter, either allowing light to pass through or blocking the light. (J., 1992)

4.3.6 SUSPENDED PARTICLE DISPLAYS
Newly developed suspended particle displays are attracting a lot of attention for both display
systems and for more general uses. These displays are electrically activated and can change
from an opaque to a clear color instantly and vice-versa. A typical suspended particle device
consists of multiple layers of different materials. The active layer associated with color change has needle-shaped particles suspended in a liquid. This active layer is sandwiched between two parallel conducting sheets. When no voltage is applied, the particles are randomly positioned and absorb light. An applied voltage causes the particles to align with the field. When aligned, light transmission is greatly increased through the composite layers. Interestingly, the color or transparency level remains at the last setting when voltage was applied or turned off. A constant voltage need not be applied for the state to remain. (Y.A. bahei-El-Din, 1998)

4.4 TYPE 2 SMART MATERIALS – ENERGY EXCHANGING

Energy fields – environments – surround all materials. When the energy state of a given material is equivalent to the energy state of its surrounding environment, then that material is said to be in equilibrium: no energy can be exchanged. If the material is at a different energy state, then a potential is set up which drives an energy exchange. All of the energy exchange materials involve atomic energy levels – the input energy raises the level, the output energy returns the level to its ground state. For example, when solar radiation strikes a photovoltaic material, the photon energy is absorbed, or more precisely – absorbed by the atoms of the material. As energy must be conserved, the excess energy in the atoms forces the atom to move to a higher energy level. Unable to sustain this level, the atom must release a corresponding amount of energy. By using semi-conductor materials, photovoltaics are able to capture this release of energy – thereby producing electricity. Note that all materials – traditional as well as smart – must conserve energy, and as such the energy level of the material will increase whenever energy is input or added. For most materials, however, this increase in energy manifests itself by increasing the internal energy of the material, most often
in the form of heat. Energy exchange smart materials distinguish themselves in their ability to recover this internal energy in a more usable form. Many of the energy-exchanging materials are also bidirectional – the input energy and output energy can be switched. The major exceptions to this are materials that exchange radiation energy – the high inefficiency of radiant energy exchange increases thermodynamic irreversibility. Furthermore, unlike most (although not all) of the property changing materials, the energy-exchange materials are almost always composite materials – exceptions include magnetostrictive iron and naturally occurring piezoelectric quartz. The following sections describe a number of commonly used Type 2 energy-exchanging materials. (Smith, 2005)

4.4.1 LIGHT-EMITTING MATERIALS
Luminescence, fluorescence and phosphorescence A definition of luminescence can be backed into by saying that it is emitted light that is not caused by incandescence,1 but rather by some other means, such as chemical action. More precisely, the term luminescence generally refers to the emission of light due to incident energy. The light is caused by the re-emission of energy in wavelengths in the visible spectrum and is associated with the reversion of electrons from a higher energy state to a lower energy state. The phenomenon can be caused by a variety of excitation sources, including electrical, chemical reactions, or even friction. A classic example of a material that is luminescent due to a chemical action is the well-known ‘light stick’ used for emergency lighting or by children during Halloween. Luminescence is the general term used to describe different phenomena based on emitted light. If the emission occurs more or less instantaneously, the term fluorescent is used. Fluorescents glow particularly brightly when bathed in a ‘black light’ (a light in the ultraviolet spectrum). If the emission is slower or delayed
to several microseconds or milliseconds, the term phosphorescence is used. Many compounds are either naturally phosphorescent or designed to be so. The amount of delay time depends on the particular kind of phosphor used. Common phosphors include different metal sulfides (e.g., ZnS). Common television screens rely on the use of ZnS. Strontium aluminate is also strongly phosphorescent. In some situations, the light emission can continue long after the source of excitation is removed because the electrons become temporarily trapped because of material characteristics. Here the term afterglow is used. Most materials that are luminescent are solids that contain small impurities, e.g., zinc sulfates with tiny amounts of copper. When these materials are exposed to incident energy in any of several forms, the energy associated with the impinging electrons or photons is absorbed by the material, which in turn causes electrons within the material to rise to a higher level. Following the descriptive model suggested by Flinn and Trojan, these electrons subsequently may fall into what are commonly called ‘traps’ associated with the impurities. 2 After a while, a trapped electron gains enough energy to leave its trap and in doing so produces a light photon in a wavelength in the visible spectrum. Its wavelength is dependent on the ion (e.g., copper) producing the trap. Thus, the nature of the emitted light and its speed and duration of emission depend upon the type of impurity present. Different properties, including the color of the emitted light, can be engineered by varying different compounds and impurity inclusions to yield specific kinds of light-emitting materials. In particular, there is a constant quest to improve the duration of the phosphorescent effect once the excitation source has been removed. Materials such as strontium aluminate, for example, have been exploited for use because of their long afterglow duration once the excitation source has been removed. Photoluminescence generally refers to
a kind of luminescence that occurs when incident energy associated with an external light source acts upon a material that then re-emits light at a lower energy level. A process of electronic excitation by photon absorption is involved. As a consequence of energy conservation, the wavelength of the emitted light is longer (i.e., ‘redder’ and involves less energy) than the wavelength of the incident light. Several kinds of phosphors photoluminescence brightly, particularly when exposed to ultraviolet light. (Smart Materials, 2000)

**Electroluminescence**

With electroluminescent materials the source of excitation is an applied voltage or an electric field. The voltage provides the energy required. There are actually two different ways that electroluminescence can occur. The first and typical condition occurs when there are impurities scattered through the basic phosphor. A high electric field causes electrons to move through the phosphor and hit the impurities. Jumps occurring in connection with the ionized impurity cause luminescence to occur. The color emitted is dependent on the type of impurity material that forms the active ions. A second and more complex behavior occurs in special materials, such as semiconductors, because of a general movement of electrons and holes. Electroluminescent materials are widely used for light strips and panels of all descriptions. The bright backlights in inexpensive watches are invariably electroluminescent panels. As noted above, colors are dependent on the active ions selected for use. In very inexpensive systems, however, simple colored filters are used to give
variety. Strips or panels can be designed to work off of different applied voltages. They can be battery operated. On the other hand, larger panels can be made to respond to household voltages.

4.4.2 BASIC SEMICONDUCTOR PHENOMENA
Basic semiconductor materials, such as silicon, are neither good conductors nor good insulators, but, with the addition of small impurities called dopants, they can be made to possess many fascinating electrical properties. The addition of these dopants or impurities allows electron movements to be precisely controlled. Exploitation of the resultant properties has allowed a semiconductor to serve the same functions as complicated multipart electronic circuitries. Silicon is the most widely used semiconducting material, although other material types are possible. Basic semiconducting materials exhibit interesting properties when surrounding temperatures are varied. Unlike most metals wherein increases in temperatures cause increases in resistance, the conductivity of semiconducting materials increases with increasing temperatures. This property already makes it quite attractive for many applications. It results from a particular type of electron band structure in the internal structure of the materials. A gap exists between bands through which thermally excited electrons cross in particular conditions. The addition of dopants or impurities creates other conditions. The role of impurities with respect to lightemitting materials was previously noted. Of importance in this discussion is the role of the impurities in affecting the flow of electrons through a material. Here again the flow is affected, but in this case in a controllable way. Silicon matrix materials are alloyed with specific concentrations of a dopant, such as boron, via a complex deposition layering procedure to form a semiconductive device. Multiple dopants of different types may
be used. The specific nature of these assemblies determines their useful electronic properties.

(Schwartz, 2002)

4.4.3 PHOTOVOLTAICS, LEDS, TRANSISTORS, THERMOELECTRICS
Many widely used devices have their fundamental basis in semiconductor technology. Here it is important to note that the basic underlying phenomenon is related to the semiconductor behavior noted above. A photovoltaic device consists primarily of a p and n junction. Instead of there being an applied voltage as described above, however, there is an incident energy (typically solar) that acts on the junction and provides the external energy input. In typical solar cells, the n layer is formed on top of the p layer. Incident energy impinges on the n layer. This incident energy causes a change in electron levels that in turn causes adjacent electrons to move because of electrostatic forces. This movement of electrons produces a current flow. Phototransistors are similar in that they convert radiant energy from light into a current. Common LEDs (light-emitting diodes) are based essentially on the converse of photovoltaic effects. An LED is a semiconductor that luminesces when a current passes through it. It is basically the opposite of a photovoltaic cell. Transistors are similarly based on semiconductor technologies. Fundamentally, a transistor can be used as a signal amplification device, or as a switching device. Thermoelectrics or Peltier devices are an electronic form of heat pump. A typical Peltier device uses a voltage input to create hot and cold junctions, hence they can be used for heating or cooling. They are found in computers as cooling devices, and in common automotive and household goods as small heaters or coolers. When in use, there must be a way provided to carry the heat generated away from the unit. In larger units, fans are commonly
used. Lasers are one of the ubiquitous workhorses of today’s technological society. Laser light occurs via stimulated emission. In a laser, an electron can be caused to move from one energy state to another because of an energy input, and, as a consequence, emit a light photon. This emitted photon can in turn stimulate another electron to change energy levels and emit another photon that vibrates in phase with the first. The chain builds up quickly with increasing intensity. Emitted photons vibrate in phase with one another. Hence the light is phase-coherent. The term ‘coherent light’ is often used. The light is monochromatic, which in turn allows it to be highly focused. Since the light occurs via stimulated emissions, the acronym Laser was adopted (i.e., light amplification by stimulated emission of radiation). (J., 1992)

4.4.4 PIEZOELECTRIC EFFECTS AND MATERIALS
In this section we enter into the world of the piezoelectric effect that forms the underlying basis for products as diverse as some types of microphones and speakers, charcoal grill fire starters, vibration reducing skis, doorbell pushers and an endless number of position sensors and small actuators. All of these devices involve use of a piezoelectric material in which an applied mechanical force produces a deformation that in turn produces an electric voltage, or, conversely, an applied voltage that causes a mechanical deformation in the material that can be used to produce a force. This general phenomenon is called the piezoelectric effect.

The piezoelectric phenomenon (piezo means pressure in Greek) was observed by the brothers Pierre and Jacques Curie when they were 21 and 24 years old in 1880. They observed that when a pressure is applied to a polarized crystal, the mechanical deformation induced resulted in an electrical charge. The phenomenon is based upon a reversible energy conversion between electrical and mechanical forms that occurs naturally in permanently polarized materials in
which parts of molecules are positively charged and other parts are negatively charged. Many naturally found crystals (e.g., quartz) possess this property, as do many newly developed polymers and ceramics. The property is curiously similar to that found in magnets where permanent magnetic polarization occurs, except here we are dealing with electrical charges. In piezoelectric materials, each cell or molecule is a dipole with a positive and negative charges onto either end. There is an alignment of the internal electric dipoles. This alignment can result in a surface charge, but this charge is neutralized by free charges present in the surrounding atmosphere. A force is applied to the piezoelectric material that causes deformations to take place, which in turn alters the neutralized state of the surface by changing the orientation of the dipoles. The reverse can also be achieved. Applying a voltage causes polarized molecules to align themselves with the electric field, which, in turn, causes a deformation to develop. The piezoelectric effect has long been exploited in many different devices. The obviously desirable property wherein a pressure produces a voltage is used in many different ways. In the common doorbell pusher, an applied force produces a voltage, which in turn is used to control an electrical circuit causing the irritating chime or delightful buzz. In the previously mentioned charcoal lighter, application of a force to a piezoelectric device causes an ignition spark. Less obvious to most people, but more widely used, are a whole host of piezo-based devices that serve as small electrically controlled actuators used in a variety of mechanical and industrial situations where in a small voltage causes a part movement that controls something else, such as a valve. The piezoelectric effect is literally instantaneous and piezoelectric devices can be quite sensitive to small pressures or voltages. Many microphones based on piezoelectric materials transform an acoustical pressure into a voltage. Alternatively, in piezoelectric
speakes, application of an electrical charge causes a mechanical deformation, which can in
turn create an acoustical pressure. (Senott, 2004)

4.4.5 SHAPE MEMORY ALLOYS
Perhaps surprisingly, eyeglass frames that are amazingly bendable, medical stents for opening
arteries that are implanted in a compressed form and
then expand to the right size and shape when warmed
by the body, tiny actuators that eject disks from laptop
computers, small microvalves and a host of other
devices, all share a common material technology. The
interesting behavior of each of these devices relies
upon a phenomenon called the ‘shape memory effect’
that refers to the ability of a particular kind of alloy
material to revert, or remember, a previously memorized or preset shape. The characteristic
derives from the phase-transformation characteristics of the material. A solid state phase
change — a molecular rearrangement — occurs in the shape memory alloy that is temperature-
dependent and reversible. For example, the material can be shaped into one configuration at a
high temperature, deformed dramatically while at a low temperature, and then revert back to
its original shape upon the application of heat in any form, including by an electrical current.
The phenomenon of superelasticity — the ability of a material to undergo enormous elastic or
reversible deformations — is also related to the shape memory effect. Nickel–titanium (NiTi)
alloys are commonly used in shape memory applications, although many other kinds of alloys also exhibit shape memory effects. These alloys can exist in final product form in two different temperature-dependent crystalline states or phases. The primary and higher temperature phase is called the austenite state. The lower temperature phase is called the martensite state. The physical properties of the material in the austenite and martensite phases are quite different. The material in the austenite state is strong and hard, while it is soft and ductile in the martensite phase. The austenite crystal structure is a simple body-centered cubic structure, while martensite has a more complex rhombic structure. With respect to its stress–strain curve, the higher temperature austenite behaves similarly to most metals. The stress–strain curve of the lower temperature martensitic structure, however, almost looks like that of an elastomer in that it has ‘plateau’ stress-deformation characteristics where large deformations can easily occur with little force. In this state, it behaves like pure tin, which can (within limits) be bent back and forth repeatedly without strain hardening that can lead to failure. The material in the lower temperature martensite state has a ‘twinned’ crystalline structure, which involves a mirror symmetry displacement of atoms across a particular plane. Twin boundaries are formed that can be moved easily and without the formation of microdefects such as dislocations. Unlike most metals that undergo deformations by slip or dislocation movement, deformation in a twinned structure occurs by large changes in the orientation of its whole crystalline structure associated with movements of its twin boundaries. The thermally induced shape memory effect is associated with these different phases. In the primary high temperature environment, the material is in the austenite phase. Upon cooling the material becomes martensitic. No obvious shape change occurs upon cooling, but now the material can be mechanically deformed. It will
remain deformed while it is cool. Upon heating, the austenitic structure again appears and the material returns to its initial shape. (Responsive Materials, 1996)

4.4.6 SHAPE MEMORY POLYMERS
Alloys are not the only materials to exhibit shape memory effects. A major effort has been recently directed with considerable success to engineering polymers to have the same effects. Applications are enormous, since polymers can be easily fabricated in a number of different forms. Medical applications, for example, include the development of shape memory polymeric strands to be used in surgical operations as self-tying knots. The strands are used to tie off blood vessels. The strands are given an initial shape, looped around a vessel and, as the body heat operates on the polymer, the strand ties itself into a knot (its remembered shape). (Responsive Materials, 1996)
CHAPTER 5: ENERGY SYSTEMS
5.1 INTRODUCTION
There are three types of energy needs in a building: thermal, mechanical and electrical. Thermal energy is necessary for heating and cooling of spaces, refrigeration, water heating and cooking. Mechanical energy is necessary for fans, motors, compressors, pumps and many appliances. Electrical energy is only directly required for lighting and peripheral equipment such as televisions and computers. These may be the needs, but the sources for supplying those needs are a different energy type altogether. There is no reasonable manner for supplying mechanical energy directly in a building, and it is not possible for any heat-rejecting need – refrigeration, space cooling – to operate without a compressor. Electrical energy, which is a relatively minor need, becomes one of the major energy supplies in a building, as it is the only source that can power mechanical equipment. Indeed, electrical energy could, and often does, take over the remaining thermal needs of heating, cooking and water heating. As a result, two thirds of a building’s energy use is due to electricity, and, perhaps even more disturbing, two-thirds of the electricity use in the United States is due to buildings. Reducing the electricity used in a building looms as one of the key targets for reducing worldwide greenhouse gas emissions. Clearly, then, developing and investing in systems that would reduce electricity use would seem to make sense, and furthermore, the unique energy transferring characteristics of many smart materials should render them ideal for building uses. This is an area, however, that has not received as much investigation as have the various lighting and facade systems. Most of the attention has been devoted to replacing part of the fossil-fuel-based electricity generation with photovoltaic generation rather than investigating new approaches for reducing energy consumption. While one might assume that the fuel mix for electricity generation is not a
building issue, as it is the regional utility that is most affected, the unit size of photovoltaics is small enough that they can easily be scaled to building size. Obviously, if the photovoltaic is connected to the electrical grid, then its specific location in the grid is not relevant. Nevertheless, photovoltaics have emerged as the front-line strategy for ‘green’ buildings. Other systems that use smart materials, particularly thermoelectrics, have received relatively little investigation as compared to that devoted to building-sized photovoltaics. (Cardwell, 1981)

5.2 PHOTOVOLTAICS
Photovoltaics were essentially the provenance of NASA until about two decades ago when large-scale photovoltaic generating facilities were first built. The high cost and low efficiency of these facilities prevented their widespread adoption as it was more effective to use the solar energy to produce steam in an intermediate step rather than to produce electricity directly. Concurrently, PVs as replacements for batteries began emerging in small products such as calculators and watches. Although PVs were commonly used in remote areas to power villages, houses and even offshore platforms without an electrical supply, they did not gain favor in grid-connected buildings until the electrical industry was deregulated. Through its ‘Million Solar Roofs’ initiative launched in 1997, the US Department of Energy has been encouraging, and rewarding (through tax credits), the widespread privatization of grid-connected PVs. Relieving the utilities of the

![Figure 10 Photovoltaic (http://www.energy.ca.gov/)](http://www.energy.ca.gov/)

65
high investment burden of moving to carbon free generation, the push for building-scale
distributed PVs was also intended to speed up the transition to solar technologies. The term
‘building-integrated photovoltaics (BIPV)’ is now a part of every architect’s vocabulary.

Some basic understanding about PV operation is needed before the decision is made to install a
system. A typical photovoltaic cell produces about 2 watts. The cells are connected in series to
form modules, and the modules are connected in parallel to form arrays. Series connection is
necessary to build up to an adequate operational voltage, but it is then vulnerable to any weak
link in the connection. If individual cells in the modules are unevenly illuminated, perhaps due
to shading from trees or dirt accumulation, the unlit cells will dissipate the power produced by
the illuminated cells. Night-time causes a problem as well, blocking diodes are necessary to
prevent PV systems from drawing electricity when they are not illuminated, but not without a
penalty. The penalty is an output power loss. As a result, the efficiency of the module is
approximately 20–25% (this is before one even takes the PV cell efficiency into account).

Thin film technologies are not subject to inter-cell losses as they are manufactured directly as
modules, but they still suffer the inverter and transformer losses. Stand-alone systems store the
generated power in batteries, whereas the intention of BIPVs is to interconnect with the utility
grid. The appropriate matching of PV operation with the utility is known as ‘balance of system’.
This is not a small issue, since both are dynamic systems. There is power conditioning
equipment that manages this transfer, but it too reduces overall efficiency. Just the inverters
for converting the DC power of the array to AC power for the utility operate at efficiencies
between 70 and 90%. (Stand-alone systems also require ‘balance of system’: batteries need
charge controllers to prevent overcharging and excessive discharging.) Each additional piece of equipment needed in the system reduces the overall efficiency. The efficiency of the individual solar cell by itself has received much of the attention in research and development. While solar cell efficiencies are continuing to increase, and are now about 8% for thin film to about 18% for single crystal silicon, we must recall that the conversion of radiation to electricity is an uphill process, and thus one in which the theoretical efficiency will be limited.8 While solar energy is certainly copious, the low efficiency would not seem to be an issue with the exception of cost, but the principle of exergy tells us that energy lost due to efficiency is converted to heat. The efficiency calculation for PVs takes into consideration solar radiation that is reflected, so not all of the efficiency drop creates heat; nevertheless, 40–45% of incident solar radiation on a module does produce heat. PVs are sensitive to heat such that as the cell temperature increases, the efficiency begins to drop, which in turn further increases its temperature. The silicon-based cells are most sensitive to heat; their maximum efficiency occurs at 0.8°C and it drops to half as the cell reaches room temperature. Standoff or rack mounting allows for passive cooling of the arrays, as all sides are exposed to air movement. Studies have shown that PVs directly mounted on building surfaces operate at 18.8°C higher than those that are standoff mounted.9 Thin film PVs are less sensitive to heat, but they are the least efficient to begin with. Regardless of the type of PV, from a single crystal to the most advanced thin film, all share concerns that include soiling and orientation. Estimated losses due to soiling vary from 5% to 10% a year. The optimum tilt angle, to minimize cosine law reductions in intensity, is 90% of the latitude of the site, and the optimum azimuth varies from due south to west depending on whether the generated power is needed for peak load production.. Given that building facades
are typically at 908, PVs installed anywhere other than on a tilted roof rack facing south will have diminished performance. (Wang, 1998)

5.3 MICRO AND MESO ENERGY SYSTEMS
Photovoltaics was the first semiconductor thermal technology to make its way into buildings, and there are currently several more coming down the pike. These newer systems, however, are intended to have a direct relationship with the building’s thermal system, i.e. heat or cool the building, rather than supply the utility. The efforts in this arena are a direct offshoot of unrelated research taking place in areas as diverse as electronics cooling and miniature battery development. The development of MEMs technology has propelled many scientists and engineers to reexamine phenomena at much smaller scales. Light, as a micro-scale behavior, can be as effectively acted on at its own scale as it can at much larger scales, and this has led to a surge in optical MEMs that use tiny mirrors to produce quite large effects. The same is true in thermal behavior. It was not until the electronics industry started applying micro-cooling for chip thermal management that processor speed was able to escape what had been seen as a thermal limit.

Thermoelectrics, or Peltier devices, became the heat sink for the chip, and when combined with heat spreaders and heat pipes, were able quickly to move heat away, particularly in laptops, where size prevented the use of a fan. It was not long before researchers began to speculate on whether these tiny heat pumps could be used for building applications as well. The initial research was directed toward the replacement of large HVAC systems with micro- and meso-scale technologies. Unfortunately, efforts were slowed for many years as the

Figure 11 Thermoelectric (http://www.nature.com/)
approach privileged the HVAC system in that the micro- and meso-scale devices were expected to produce the same behavior. One group of researchers simply ganged thermoelectric together in series to produce a closet-sized system that could be directly substituted for a building heat pump. While the system worked, its efficiency was quite low, as thermoelectrics, regardless of their remarkable qualities, are still uphill processes, thermodynamically speaking. Another group of researchers went in the other direction, repackaging the meso-scale thermoelectrics as a micro-scale film. Their concept, an interesting one, was to produce a sheet of heat pumps that could be applied in rooms just like wallpaper. Nevertheless, they were still thinking subordinate to the existing technology, and abandoned the project when the sheet was unable to match the behavior of a conventional HVAC system.

Micro- and meso-scale research of thermal technologies has since retreated, and currently efforts are being focused on better scale matching of devices and behaviors. Researchers have recognized that the HVAC system is an anomaly, and these small devices could be more effectively used if deployed directly on the object that needs the thermal management, rather than indirectly through the surrounding environment. While still not available for building uses, these technologies will soon profoundly affect the constituency of our thermal environment. Soon to be available, however, are micro-heaters, although their current size, about that of the palm of one’s hand, puts them more in the meso-range. (Schenieder, 2000)

These devices are ideal for water heating, and other direct uses such as baseboard heating. Meso fuel cells are being developed, and they will have many potential uses, particularly the powering of larger devices. Point loads, such as lighting and computers, could be controlled directly, insulation could be turned on and off by altering its thermal profile, and contaminated air could be corralled and separated from the occupants. The enormity of the possible change requires that both engineers and architects be willing to let go of the constraints of conventional practice.
CHAPTER 6: STRUCTURAL SYSTEMS
6.1 INTRODUCTION
Structures behave in complex ways when subjected to forces that originate externally to the structure (winds, earthquakes) or are due to its use context, or even its own dead weight. Specific members, for example, bend or tend to buckle. Connections tend to shear apart. Whole structures move about in different modes during dynamically acting earthquake or wind loadings. Designers have been studying these phenomena for hundreds of years, and by now the structural design profession is quite a sophisticated one. The field is strengthened by many computer-based structural analysis simulation programs that help a designer predict the behavior of even the highly complex structures under loadings. Nonetheless, there are still many problematic aspects to designing safe and efficient structures for necessary strength and stiffness criteria. For example, providing safe structural responses to wind and earthquake loadings that produce complex dynamic effects in structures remains challenging. The field of smart materials has opened up some new avenues for solving some old problems in structures, while at the same time opening up some new design possibilities that extend to new areas called ‘smart structures’. One of the fascinations that the field of structures has for many designers is that structural configurations seem to acquire an active life when subjected to forces associated with external loadings (wind, earthquakes), their use context (occupancy loads) or their own self-weights. They change shapes, they move back and forth. They tend to bend, and sometimes break. The by now tired analogy so often cited of how a building or bridge structure works by comparing it with that of the skeleton of human body still serves a useful purpose when considering what a ‘smart structure’ might be. In the analogy, however, there is a suggestion that the skeleton alone provides the human with its structural capabilities,
which is obviously wrong. There is a whole system of other sensing and actuating elements that are interconnected with the skeleton, e.g., tendons and muscles. Without these interconnected elements, the skeleton would collapse. The overall system is not a static one – there are many active actions – e.g., muscles that contract and exert forces at critical locations – that provide responses to even the simplest changing external condition. Consider the complexity of the human body’s response when a human reaches out to pick up even a small weight at arm’s length. Not only do the arm structures spring into action, but literally the whole body does as well, including stance changes. Many of these actions can occur literally instinctively and exhibit what might easily be called ‘smart behaviors’ and are associated with what are now generally called ‘smart structures’. There are also other responses and more general strategies; however that might be dictated by the human’s intelligence. Knowing that an unusual operation is in the offing, for example, a human might choose to reposition his or her stance a priori in order to better accommodate the impending condition. In these cognition-controlled processes, we have a suggestion of what might be called an ‘intelligent structure’ of the kind described in the following chapter. In this section we begin considering what is realistically meant at the present time by the term ‘smart structure’. We begin with a series of techniques, now generally called ‘structural health monitoring’, which serve continuously to monitor a structure for any damage that may be present. The idea is an attractive one. In much the same way that our body detects a problem with a sprain, a broken bone, or a cut, it is easy to imagine structures with capabilities for monitoring their own health and providing various alerts to users as a prelude to suitable responses. One of the exciting new developments in this general area is the development of what might be called ‘smart skins’. These are surface structures that have
sensing capabilities throughout their extents. For example, there have been experiments with micro-sized piezoelectric particles distributed throughout a surface that detect when abrasions occur. Using the very stuff of the material itself to provide a sensing and reporting function is suggestive of what a ‘smart structural material’ might ultimately become. (Huang, 2003)

Following the section on structural health monitoring, ways of controlling vibrations and other phenomena of concern in a structural design context are explored. In general, most current approaches to smart structures have as their objective a capability for sensing an outside effect and providing a suitable structural response to it. In the following, both passive and active smart structures are reviewed. A passive system normally has the objective of minimizing the effects of an unwanted phenomenon through the simplest responsive means possible. An active system generally means that a means of controlling an unwanted phenomenon is provided via force applications or other techniques. Current approaches typically consist of the structure, a sensor system, an actuator system and a control system. The control system includes a microprocessor that analyzes input data, relates it to a mathematical model of the structural behavior of interest, and sends out suitable output signals to the actuator systems that provide requisite balancing or responding forces. The continued development of smart materials may ultimately allow many of these functions to be integral to the structure rather than exist as separate components. (Huang, 2003)

6.2 CONTROL OF STRUCTURAL VIBRATIONS
We have seen in the previous section that there are ways of assessing what damages might occur in structures. There are also ways of preventing the damages in the first place via different active control approaches that are designed to provide forces, stresses or
deformations that in some way balance or offset those causing the damage, or which change the vibration characteristics of a structure to prevent unwanted and damage-causing phenomena of this kind. In this section we will look at vibration control. This is a huge topic with a long history. Various kinds of prestressing techniques, for example, have long been used to control wind-induced dynamic flutter in cable structures; or, it is well known that huge tuned mass dampers have been installed in the upper floors of tall office buildings as a way of damping the lateral motions caused by winds that both threatened the structural integrity of the building or caused occupant discomfort. This section will not cover these many well known applications, but rather focus on newer developments associated more specifically with the use of smart materials.

The control of vibratory phenomena has been a central objective of many research and development efforts in the smart materials area. Vibratory phenomena may arise from external forces (winds, earthquakes), from machinery carried by a structure, from the human occupancy of the building, or other sources. Effects of vibrations vary. On the one hand, they may simply be troublesome nuisances that cause human irritation or discomfort. On the other hand, vibrations induced in buildings or bridges by earthquake or wind forces can potentially cause catastrophic collapses because of the dynamic forces generated in the structures by the accelerations and movements associated with vibratory motions. (Lightman, 2003)

**Piezoelectrics**

Piezoelectric devices have proven effective because of their capabilities for serving both as sensors and actuators. Both passive and active approaches are in use. Passive systems assume a variety of forms, but generally use one piezoelectric device bonded to a member. One approach
is often called ‘shunt damping’. A piezoelectric device changes mechanical energy associated with strain deformations to electrical energy. The resulting output signals from the piezoelectric transducer are picked up by a specially designed impedance or resistive shunt, which in turn causes the electrical energy to dissipate. This results in a damping action. These devices are relatively hard to control, and are generally designed to work at specific targeted modal frequencies. ‘Piezoelectric skis’ provide an interesting product design example of an energy dissipating system. The problem of vibrating (‘chattering’) skis is well known to advanced skiers. As skis vibrate, they lift off the snow causing a loss of contact and thus a loss of control. Several companies have developed passive piezoelectric damping systems that are built directly into skis. The bending of a ski creates output electrical energy that is shunted to an energy dissipation module that in turn reduces vibration. The vibration control unit is placed just in front of the binding, where bending is maximal. (Alloys and Materials, 2002)

Other kinds of piezoelectric technologies include the use of piezoelectric polymers and the development of piezoelectric damping composite materials. The composite materials are intended to serve as passive self-damping surfaces. Piezoelectric rod-like elements are dispersed throughout a viscoelastic matrix. Conductive surface materials serve as electrodes to pick up output signals. These materials are proposed for use in different ways for damping. Active actuator patches are also proposed.
**Electrorheological and magnetorheological materials**

A viscous fluid is rather like a semifluid. It can be thick and, according to Webster’s Third, suggestive of a gluey substance. Highly viscous materials (such as heavy oil) do flow, but more slowly than do liquids such as water. A viscoelastic material exhibits properties of both viscous and elastic properties. Many conventional dampers (e.g., including many common cylinder/piston/valve devices) use viscoelastic fluids as a primary energy absorption medium. These devices are typically designed for a specific target frequency range and may not be effective outside of that range. Many fluid materials have particularly pronounced rheological properties (i.e., properties of flowing matter) that make them ideal candidates for use in vibration control applications. Smart rheological fluids have properties that can be reversibly altered by external stimuli. Thus, the level of viscosity of electrorheological (ER) materials can be varied by electrical stimuli, and that of magnetorheological (MR) materials can be altered by varying the surrounding magnetic field. Since the viscosity of these materials can be altered, damping devices utilizing them can be designed to be tuned to varying frequency ranges. Since the smart materials used are based on electrical phenomena, and respond very quickly, viscosities can be controlled quite well and be programmed to respond to varying conditions obtained from sensory data and/or analytical vibration models. The physical make-up of these kinds of smart dampers varies widely. In some systems either electrorheological or magnetorheological fluids may be encased in laminates that are applied to structures in different ways, and which are connected to a control microprocessor. Varying the electrical or magnetic stimuli causes the laminate to stiffen or become more flexible, thus altering the vibratory characteristics of the base structure. While still far off, the idea of making a whole laminated surface with inherent damping capabilities is not without feasibility. (Gandhi, 1992)
Other materials
Virtually any material that undergoes reversible shape or stiffness changes could conceivably be used for vibration control, since any change in these parameters would influence overall vibration characteristics. The use of shape memory alloys, for example, has been explored in connection with vibration control; particularly for small-sized applications. Their slow response characteristics, however, make them suitable for only limited applications.

6.3 CONTROL OF OTHER STRUCTURAL PHENOMENA
Most of the discussion thus far has focused on vibration control, since this is one of the current major application domains for smart materials. Many other structural phenomena, however, can also be controlled. Engineers have long sought to control problematic static deflections of beams or larger frameworks via various kinds of static prestressing techniques. Thus, a reinforced concrete beam might have embedded prestressing cables that cause the beam to camber upwards to offset downward deflections induced by external loadings. There have been attempts to vary prestressing forces in response to the level of the externally induced deflection.

Truss members have had actuators built into specific members to alter force distributions and related deflections. Various shape-changing smart materials could possibly be used in many of these applications. The active paired sensoractuator piezoelectric systems described previously for vibration control, for example, could be used to control beam or framework deflections by developing forces that balance or counteract those generated by externally acting loadings. These systems have also been experimentally used to control incipient buckling of slender members. Shape memory materials could also be used. Experiments have been made with
devising active truss structures for large flexible space structures via the use of piezoelectric technologies. (Livingstone, 2002)
CHAPTER 7: LIGHTING SYSTEMS
7.1 INTRODUCTION
The production of artificial (electrical) light is the most inefficient process in a building. As such, there has been a concerted effort to improve the efficiency of the individual lamps. Fluorescents are up to five times more efficient than incandescents, and high intensity discharge (HID) lamps are twice as efficient as fluorescents. The production of light from electricity is what is known as an uphill energy conversion, and thus the theoretical efficiency is extremely low. The efforts devoted to improving lamp efficiency are netting smaller and smaller energy savings as the theoretical limit is being approached. Smart materials can have a major impact on energy use, even insofar as they are not that much more efficient at producing light than are conventional systems. The fundamental savings will come from the lighting systems that smart materials enable, rather than from any single illumination source. The current approach to lighting was developed nearly a century ago, and like HVAC systems has seen very little change. Ambient lighting, or space lighting, emerged as the focus of lighting design, and it has remained as that focus, even as we have learned much more about not only the behavior of light, but also the processes of the human visual system. Ambient light privileges constancy, and as perhaps an enigmatic result, the more ambient light that is provided, the more task light someone will need in order to see. Although the understanding that contrast in light levels is more important than the level itself is now becoming more widespread, existing lighting technology remains geared toward ambient light. The beam spread of fluorescents demands a regular pattern of fixtures, and the intensity level of HID lamps requires a mounting height far above eye level. In the late 19th century, as artificial lighting began to enter the marketplace, incandescents were described as being able to ‘divide’ light. This idea of division was in stark
contrast to the dominating light produced by the preeminent arc lamp, the intensity of which was so high that entire streets could purportedly be illuminated with a single lamp. A century later, we return to this idea of division, looking to smart materials to enable a discretely designed lighting system that allows for direct control of light to the eye, rather than light to the building. (Wikipedia Smart materials, 2009)

7.2 FIBER-OPTIC SYSTEMS
We start with fiber-optics even though they are not technically smart materials; no transformation takes place in a fiber-optic, it is only a conduit for light. The use of fiber-optics for illumination, however, demands a radical shift in the way one thinks about lighting. Each optical cable will emit a fraction of the light emitted from a more typical lamp, but the light can be more productive. Ambient lighting systems fall prey to inverse square losses, the intensity drops off with the square of the distance. The light-emitting end of the fiber-optic can be placed almost anywhere, and thus can be quite close to the object or surface being illuminated. The tiny amount of light emitted may deliver the same lumens to the desired location as light being emitted from a ceiling fixture at more than an order of magnitude greater intensity. Contrast can also be locally and directly controlled. As we can see, then, fiber-optic lighting possesses two of the important characteristics of smart materials – they are direct and selective. Fiber-optic lighting offers other advantages over conventional systems. The source of light is remote in comparison to

Figure 13 Fiber optic section
(http://talesofacoldadmin.files.wordpress.com/)
where it is delivered. As a result, the heat from the source is also remote. Lighting, as an
inefficient process, produces more heat than light such that about one-third of a building’s air-
conditioning load is simply to remove the excess heat generated by the lamps. Not only does a
remote source save energy, but it protects the lighted objects from heat damage and possibly
even fire. Since no electrical or mechanical components are required beyond those at the
source location, electrical infrastructure can be reduced and maintenance is simplified. Color
control and UV/IR filtering can easily be incorporated, expanding the versatility not only of the
system but of each individual cable. These advantages, particularly in regard to the heat
reduction and UV control, have rendered fiber-optics the choice for museum exhibit lighting
and for display case illumination. The majority of other architectural uses, however, tend to be
decorative, utilizing the point of light at the emitting end of the cable as a feature rather than
for illumination. Even though there are good models for the effective and efficient use of fiber-
optic illumination, the paradigm of the ambiently lit interior is so pervasive that only those
applications with critical requirements have utilized this discrete approach to lighting. (Linberg,
1978)

A fiber-optic lighting systems is comprised of three major components:

* Illuminator: this houses the light supply for the fiber-optics. The source of light can be
anything, from LEDs to halogen, metal halide, or even solar radiation. Key features of the
source are its color and intensity; the greater the intensity, the greater the number of emitting
ends, called tails, that are possible. Greater intensity also enables longer length of the tails, up
to 75 feet. The light source generates a large amount of heat which then must be dissipated by
heat sinks and/or fans. Reflectors and lenses will narrow the light beam as much as possible to
fit within the cone of acceptance (this is determined from the critical angle of the strand medium). Light must enter the acceptance cone, so the more collimated the source, the more efficient the transformation will be. Color wheels and other filters are often included in the illuminator to create special lighting effects or eliminate unwanted UV. Electronic controls, including ballasts and dimmers, are also housed in the illuminator. (Mark J. Schulz, 2005)

* Cable or harness: fiber-optics for lighting are either solid core or stranded fiber, both of which are bundled into cable form and sheathed with a protective covering. (No cladding is used.) The emitting end will most likely be split into multiple tails, each one providing distinct illumination, while the source end will be bound as a single cable and connected into a coupler, which is then connected to the illuminator. The entire cable assembly, including the coupler, is referred to as a harness.

* End fittings: for end emitters, the tail ends will need to be secured or mounted in some manner, and the primary purpose of the end fittings, which are usually threaded, is to allow this. The fittings can also house individual lenses and filters so that the light emitted from each tail end can be controlled separately.

7.3 SOLID STATE
Solid state lighting is a large category that refers to any type of device that uses semiconducting materials to convert electricity into light. Essentially the same principle that drives a photovoltaic, but operated in reverse, the solid state mechanism represents the first major introduction of a new mode of light generation since the introduction of fluorescents at the
1939 World’s Fair. In this category can be found some of the most innovative new smart technologies, including organic light-emitting diodes (OLEDs) and light-emitting polymers (OLPs), but the workhorse technology, and by far the largest occupant of this group, are inorganic light-emitting diodes (LEDs). The use of LEDs for task lighting, signage, outdoor lighting, facade illumination, traffic signals, mood lighting, large panel displays and other applications is a far cry from the 1980s when LEDs were primarily used as indicator lights, letting us know that our oven was on, or that our car alarm had been activated. (Leo, 2007)

We might consider LEDs as the ‘smart’ version of fiberoptics, as, in addition to being discrete and direct, they are also self-actuating, immediate and transient. Furthermore, while fiber-optics allow for the division of light, LEDs allow for its recombination in arrays of any multiple. We could almost consider fiber-optics as an intermediate placeholder for the spot that will eventually be taken over by LEDs. The advantages of LEDs over any other commercially available lighting system are profound. Besides their small dimensions which allow their deployment in spaces unable to be illuminated with any other means (fiber-optics still must be tethered to a rather large illuminator), the spectral qualities of the light can be precisely controlled, eliminating both the infrared radiation that accompanies incandescents and the ultraviolet radiation that is associated with most discharge lamps. Beam spreads can be controlled or concentrated at the source, reducing the need for elaborate luminaires with large filters, reflectors and lenses. Considered as their largest drawback is their low efficacy, which at about 20–30 lumens/watt still beats out the typical incandescent. (Leo, 2007)
CHAPTER 8: FAÇADE SYSTEMS
8.1 INTRODUCTION

Facade systems, and particularly glazing, pose an intractable problem for designers. The facade is always bi-directional in that energy transfers in both directions simultaneously. Heat may be conducting to the outside while radiating to the interior, and light entering the building must be balanced with the view to the exterior. The problem of glazing did not emerge until the twentieth century, as it required the development of mechanical HVAC systems to enable the use of lighter weight and transparent facades. At first, the facade systems, albeit lightweight and with an unprecedented amount of glazing, were more opaque than transparent. Constant volume HVAC systems coupled with perimeter systems were more than adequate for mitigating the highly variable thermal loads of the facade, and simple shading devices were used to manage glare. The advent of the energy crisis in the 1970s marked the phasing out of the energy intensive HVAC systems and their replacement with Variable Air Volume systems. The energy penalty was removed, but at a cost to the thermal stability of the facade which began to loom as a problematic element in the building. Paradoxically, the demise of the CAV system was coupled with a rise in the percentage of glazing on the exterior, further exacerbating the thermal and optical swings of the facade. Compensatory mechanisms and approaches were developed and experimented with, and a host of new technologies were incorporated into the facade or enclosure systems. Glazing was coated with thin films, including low-emissivity, solar reflective, and non-reflective (on the interior faces). Automated louvers were installed in conjunction with energy management control systems to reject excess solar radiation, and elaborate double skin systems, which wrap the building twice in glazing, were encouraged for the dampening of the thermal swings. As a result, no other group in the architecture field has embraced smart materials as wholeheartedly as have the designers and engineers responsible for facade and enclosure systems. (Vardan, 2006)

Smart materials were envisioned as the ideal technology for providing all of the functions of the super facade, yet would do so simply and seamlessly. Visions of Mike Davies’ ‘Polyvalent Wall’ – a thin skin
that combined layers of electrochromics, photovoltaics, conductive glass, thermal radiators, micropore gas-flow sheets and more – served as the model of the ultimate facade. In 1984, the seminal theoretician and historian Reyner Banham, while commenting that a ‘self-regulating and controllable glass remains little more than a promise’, did conclude that if the real energy costs were taken into account, the new technology would prove to be economically viable.2 His prediction was not far off, as an entire field devoted to the development of smart windows and facades has been premised on their contribution to energy efficiency.

8.2 THE SMART WINDOW
The term ‘smart window’ has been applied to any system that purports to have an interactive or switchable surface, regardless of whether that surface is a real or virtual window, interior or exterior. ‘Smart’ windows will typically possess one or more of the following functions:

* Control of optical transmittance. A shift in the transparency (the optical density) of the material may be used to manage the incident solar radiation, particularly in the visual and near ultraviolet wavelengths. The window would vary from high density (opaque or translucent) for the prevention of direct sun penetration and its associated glare to low density (transparent) as incident light loses intensity.

* Control of thermal transmittance. This is a similar function to that above, but the wavelengths of interest extend into the near infrared region of the spectrum. Heat transmission by radiation can be minimized when appropriate (summer) and maximized for other conditions.

* Control of thermal absorption. Transparency and conductivity tend to correlate with each other, but are relatively independent of the incident radiation. Whenever the inside temperature is higher than the outside temperature, a bidirectional heat flow is established: radiant energy transfers in, while thermal
energy transfers out. Altering the absorption of the glazing will ultimately affect the net conductivity, and thus can shift the balance in favor of one or the other direction.

* Control of view. The use of switchable materials to control view is currently the fastest growing application of smart materials in a building. Interior panels and partitions that switch from transparent to translucent allow light to transmit, but are able to moderate the view by altering the specularity of the material. Exterior store fronts can reveal merchandise in windows selectively, perhaps only when the store is open. A specular material will transmit intact images, whereas a diffuse material will obscure the image.

<table>
<thead>
<tr>
<th>System type</th>
<th>Spectral response (bleached to colored)</th>
<th>Interior result visual</th>
<th>Interior result thermal</th>
<th>Input energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photochromic</td>
<td>Specular to specular transmission at high UV levels</td>
<td>Reduction in intensity but still transparent</td>
<td>Reduction in transmitted radiation</td>
<td>UV radiation</td>
</tr>
<tr>
<td>Thermochromic</td>
<td>Specular to specular transmission at high IR levels</td>
<td>Reduction in intensity but still transparent</td>
<td>Reduction in transmitted radiation</td>
<td>Heat (high surface temperature)</td>
</tr>
<tr>
<td>Thermotropic</td>
<td>Specular to diffuse transmission at high and low temperatures</td>
<td>Reduction in intensity and visibility, becomes diffuse</td>
<td>Reduction in transmitted radiation, limited radiation, and conductivity</td>
<td>Heat (high and/or low surface temperature)</td>
</tr>
<tr>
<td>Electrochromic</td>
<td>Specular to specular transmission toward short wavelength region (blue)</td>
<td>Reduction in intensity</td>
<td>Proportional reduction in transmitted radiation</td>
<td>Voltage or current pulse</td>
</tr>
<tr>
<td>Liquid crystal</td>
<td>Specular to diffuse transmission</td>
<td>Minimal reduction in intensity, reduction in visibility, becomes diffuse</td>
<td>Minimal impact on transmitted radiation</td>
<td>Voltage</td>
</tr>
<tr>
<td>Suspended particle</td>
<td>Specular to diffuse transmission</td>
<td>Reduction in intensity and visibility, becomes diffuse</td>
<td>Minimal impact on transmitted radiation</td>
<td>Current</td>
</tr>
</tbody>
</table>

* indicates that a control system and associated electrical supply are required

![Figure 14 The Smart Window system chart (http://physics.unc.edu/)](image-url)

Thermochromics are more amenable to the heat issue, but do so by sacrificing control in the visual part of the spectrum. As heat is the activating energy input, thermochromic glazing operates best in the near infrared region of the solar spectrum. The desired switch point is usually set to the interior temperature so that as the temperature of the glazing begins to rise – due either to absorption of solar radiation or to
high external temperature – the radiant transmission is reflected rather than transmitted. The application hurdle that thermochromic glazing must overcome is its low transmissivity in the visual part of the spectrum, which currently ranges from about 27 to 35%.3 Given that the primary reason for a glazed façade is the view, and secondarily, the provision of daylight, thermochromics have been little utilized in the development of smart windows. Thermotropics respond to the same environmental input as do thermochromics, but the difference in the internal mechanism has given thermotropics broader potential application. Whereas thermochromics switch from transmissive to reflective, thermotropics undergo a change in specularity, resulting in the ability to provide diffuse daylight even as the view is diminished. One feature they offer that is relatively unique is the ability to change the conductivity of the glazing as well as its transmissivity. The phase change that is at the core of any thermotropic results in a substantial reconfiguration in the structure of the material, such that a quite significant change in thermal conductivity could take place. This effect is more pronounced when a hydrogel is used to fill a cavity in double glazing as compared to using a polymer foil as the thermotropic.4 Some hydrogels can further have two transition states, turning opaque at low as well as high temperatures, rendering them useful for preventing radiant loss from the interior during the winter. Although not nearly as commercially available as the various electrochromic glazing systems, they are expected to become popular for any kind of application, such as skylights, where light rather than view is paramount. (Ritter, 2007) (Rafel, 2002)
CHAPTER 9: THE SMART BUILDING CONCEPT AND ITS IMPLICATION
9.1 INTRODUCTION
The building parts and the building materials we discussed in the earlier chapters will be used in this chapter to derive a conceptual building type. As such the materials and the construction technology used in this type is based on the studies by different sources. The studies which can be just factual in resemblance to any built project till date.

The process of building starts from the foundation and get completed with time till the human inhabittance takes place. With time the wear and tear factor of the building increases and it is liable to different types of structural threats. The first type of buildings was built way before the birth of the Christ but still the same procedure is used for building the new future and with more or less the same building materials. The problems with the building structure like fire, earthquake are still the same and are taken in the same way by the architects around the world. The changing cities and metropolitans are ruining the natural environment suited for a human. In this era of information technology revolution the home of future is not taken into consideration at all. We have a whole set of materials in front of us which can respond to our demands and a technology which can even sense our emotions. But sadly we are still using the same way to live our life.

The built environment can become interactive with humans in three main ways. There are interactive systems that describe the environment in which the person occupies, systems that define and alter space according to the user, and systems that directly communicate with a person or allow for communication between people. Interactive architecture is made possible through the use of micro-controllers, sensors, and actuators. Advancements in electrical and mechanical engineering, material innovation, and fabrication techniques such as computer
numerically controlled (CNC) fabrication, have made many concepts in the kinetic architecture realm come to existence. Interactive systems that portray the environment can be a beautiful aesthetic addition to a structure. These systems can convey a wide variety of information about the surrounding environment of a building or building component. Most of these systems detect where people are, and somehow display this information to the public; it is basically a traffic graph. Therefore, the system is describing to the public where other people are and what they are doing.

When we build a project the energy consumption is taken in account according to the construction techniques and further according to the human usage. This part of energy is shared from the same source for a definite population. For example, for a city like New York the major energy is been used by the population for its comfort, which can be subdivided into many categories like entertainment, transport etc. This energy is been generated from many sources like coal, petroleum, sun, wind etc. Many of them are renewable and some are not. But the problem with the present generation is that the energy sources in use are majorly non renewable and they tend to finish by elapse of time and usage. The world is facing this energy crisis since the last few decades but the present generation is still not responding to it on the right manner. The natural processes and the environmental factors are very much renewable but still they are not used in constructing the charging grounds of small cells for human usage.
9.2 CASE STUDIES

9.2.1 EMILIO PINERO

In the early 1960s, Emilio Pinero pioneered the use of scissor mechanisms to make deployable structures. A mechanism can expand in a horizontal direction, in both horizontal and vertical directions, and with a fabric covering, which unfolds with the mechanism to complete a deployable roof. Chuck Hoberman who has followed Pinero’s way is another “inventor”. (Robbin, 1996).

He calls himself the designer of several kinetic structures and seeks for new spatial organizations based on the idea of motion in nature. In his structures “the idea of mechanism” can be clearly seen both in the structural relations and the way deployments are achieved with successfully. But the majority of those structures are “installations” rather than they are part of the structural design in building scale. Since in those days technology was far behind to experiment on large scale. (Wikipedia Smart materials, 2009)

Figure 16 Emilio Pinero 1 (http://www.hoy.es/)

Figure 15 Emilio Pinero 2 (http://www.hoy.es/)
9.2.2 KUWAIT PAVILION
Kuwait Pavilion was built in 1991-1992 and it is a symbolic structure which was commissioned at the behest of the emirate for the 1992 World’s Fair in Seville, Spain. The roof structure is made up by mobile elements which come together as tapered fingers of two hands, or better in this case, as the leaves of two palm branches. Seventeen 25 meter long finger elements, constructed in timber and supported by hydraulically operated reinforced-concrete columns, interlock to form an impenetrable vault and then unfold to reveal the gentle barrel-shape of the 525 square meter piazza. The piazza is glazed with panels of laminated structural glass and translucent marble that illuminate the gallery bellow during the day and grow with an enigmatic inner light at night when uncovered. When half closed, the roof casts light and shadow on the piazza bellow, providing protection from the sun, like a palm shaded oasis. (A. Tzonis)

9.2.3 FOLDING EGG
The Folding Egg is a prototype kinetic folding sheet created by the Kinetic Design Group of Massachusetts Institute of Technology. This structure is made by low-cost recyclable material and is essentially a collapsible three dimensional truss structure. It has a structural
stability and many possible configurations. The basic principles and shape that this construction uses are not newly formed but have been explored in previous years with different constructions. Examples can be seen in where a church and a model have been built over the same principles. Generally it can be said this kind of constructions belong to the optimized in efficiency constructions. However, the Folding Egg differs from these structures as additionally it has the ability to reconfigure itself through kinetic movement.

9.2.4 HELIOTRROPE (HOUSE)
Built originally in 1994 as the private residence and special project of Rolf Disch, the Heliotrope is a one-of-a-kind design. The Heliotrope in Freiburg was the first building in the world to create more energy than it uses, of which is entirely renewable, emissions free and CO2 neutral. The structure physically rotates to track the sun, which allows it to harness the maximum natural sunlight and warmth possible. Several different energy generation modules are used in the building including a 603 ft. sq. dual-axis solar photovoltaic tracking panel, a geothermal heat exchanger, a combined heat and power unit (CHP) and solar-thermal balcony railings to provide heat and warm water. These innovations in combination with the superior insulation of the residence allow the Heliotrope to produce anywhere between four to six times its energy usage depending on the time of year. The Heliotrope is also fitted with a grey-water cleansing system and built-in natural waste composting.

Figure 19 Heliotrope House (http://nano-cabin.com/)
At the same time Freiburg’s Heliotrope was built, Hansgrohe contracted Rolf Disch Solar Architecture to design and build another Heliotrope to be used as a visitor’s center and showroom in Offenburg, Germany. A third Heliotrope was then contracted and built in Hilpoltstein, Bavaria to be used as a technical dental laboratory. Disch’s unique design accommodates different utilization from private residences to laboratories, and nevertheless maintains the structure’s positive energy balance. In addition to the original Heliotrope design, Rolf Disch has drawn plans for larger versions of the project to be built as a rotating hotel, which gives every guest a beautiful view, as well as administrative buildings and even an exhibition pavilion for the EXPO 2010 in Shanghai.

9.2.5 INTERACTIVE FAÇADE

Interactive Façade was designed by Michael Fox and Axel Kilian of the Kinetic Design Group of the Massachusetts Institute of Technology. This interactive system “fosters direct interaction between an architectural - scale installation and pedestrian activity on the street. The 160’ long band of responsive ‘whiskers’ that will wrap around the building in the heart of Manhattan allows pedestrians to walk up and interact with the installation.”2 These whiskers are long poles that extend outward from the façade of the building and sense the presence of people in motion, and in a “wave-like rhythm”3 they will follow the pedestrians. An observer when looking upon the structure can see these arms tracking people while they move past the building. This project is certainly a kinetic system that
describes the environment. Through the use of sensors, the façade system is able to detect the pedestrian movement below, and mimic this movement to create a traffic graph that is displayed to the rest of Manhattan. (Thakur, 2010)

9.2.6 INSTITUTE DU MONDE ARABE
The AWI is located in the building also known as Institute du Monde Arabe, on Rue des Fossés Saint Bernard in Paris, France, constructed from 1981 to 1987 with a floor space of 181,850 square feet (16,894 m²). Designed by Jean Nouvel. The huge south-facing garden courtyard wall has been described as a 60m 'Venetian blind', although its appearance is more patently Islamic in decorative terms. It is, however, an ocular device of striking originality, made up of numerous and variously dimensioned metallic diaphragms set in pierced metal borders. These diaphragms operate like a camera lens to control the sun's penetration into the interior of the building. The changes to the irises are dramatically revealed internally while externally a subtle density pattern can be observed. Thus the whole effect is like a giant Islamic pierced screen, giving significance and an audacious brilliance to this remarkable building. (Thakur, 2010)

9.2.7 TOPOTRNSGERITY - NON - LINEAR RESPONSIVE ENVIRONMENTS
Following on from some of the ideas in the previous post Topotransegrity designed by Robert Neumayr explores how a responsive architecture can be introduced in public spaces challenging long-held assumptions about architecture as a passive arrangement. It investigates today’s networked ways that enable architecture itself to operate as an intelligent interface that
connects spaces, users and performance criteria in real time and the impact such spatial configurations have on urban space and urban public life.

*Figure 22 Topotransegrity (http://vanguardq.wordpress.com/)*

Topotransegrity is a kinetic structure, which constantly evaluates its surroundings and reconfigures according to these changing conditions. It is a generic responsive structural system, which adapts to isolated spatial requirements. The structure is capable of various transformations, which range from small-scale surface articulations to large surface deformations, which can generate temporary enclosures. Such a responsive structure can multiply. Intensify and vary the potential uses of public spaces, which usually rely on external intervention to host new activities. Sensors, input devices and wireless networks are integrated into normally dead building materials to transform architectural space into complex intelligent operating systems.

The programme mode automates the basic functions of the structure. Directly related to the specific event schedule of its environment it drives the generic transformations, initiating and locating the deformations that control the access and the circulation within the public spaces. It also generates small emergent temporary spaces, which host ancillary programmes related to ongoing events. Finally it enables certain tiles of the structure’s sheared surface to pivot and thus allow for temporarily different degrees of transparency within the structures spatial arrangement. The crowd mode responds in real time to the movements and behavioral patterns of the visitors within the structure. It influences the size, orientation and development
of the temporary enclosures, previously established by the programme mode. Finally it affects the orientation of the surface’s tiles, based on the positions and sizes of the visitor crowds. Finally the memory mode records, on a long-term basis, the paths and motion patterns chosen by Individual users, influencing the surface topography by indicating and leveling the most frequented parts. It defines the actual width of circulation spaces, temporary level connections, entrance areas and thresholds according to the number of visitors at every point in time during the period of use. These three parallel modes of operation run simultaneously and add up to the structure’s complex, unpredictable user-dependant spatial configuration. The constantly changing three-dimensional space envelope interacts with its visitors in a permanent feedback loop, where the users reactions to spatial adaptation are fed back into the system to in turn update the spatial arrangements and individually customize the built environment to requirements at any given moment for any given pattern of use. (Thakur, 2010)

9.2.8 ENTERACTIVE
Enteractive, located on the corner of 11th Street and Flower Street in Los Angeles and designed by Electroland, is an interactive system that also displays pedestrian traffic information to the public, but in a much different fashion than Interactive Façade. Located in the entry walkway of the building, there is a large grid of illuminated squares.
If a person steps on a square that is in the illuminated state, other squares light up in a beautiful pattern. The pattern that is shown depends on the amount of people and their location on the grid, as well as the position of the illuminated squares. If enough people perform the tasks the grid wants all of the squares will light up, giving a sense of accomplishment to the user. This project consists of “environmental intelligence and surveillance of human activity...combined with a video-game sensibility.” There are televisions located in the lobby that display the activity occurring on the grid. This information is also displayed on the exterior façade of the building for the city of Los Angeles to view. The façade also consists of a grid of illuminated squares which replicate the lobby floor. As a person interacts with Enteractive, they are not only changing the pattern on the floor, but they are changing the façade pattern as well. This project is one of the best examples of congregating the built environment with people. A person truly has control over what is displayed onto the exterior façade for the surrounding community to view. Interactive Façade and Enteractive both interact with their surrounding environments, and reveal the processed information to the community. Though achieved in different manners, both systems accomplish the same goal. Interactive Façade follows people as they walk by the structure, and allows the public to view the traffic pattern. Enteractive tries to dictate traffic by enticing users to step on certain squares, and then portrays the results to the community. Despite their differences in
the methods of actuation, both systems are basically devices that demonstrate the pedestrian movement within the system’s surroundings.

9.2.9 Bubbles

Bubbles was designed and built by a rather large team of people including Michael Fox, Jintow Lin, Axel Kilian, Scott Franklin, and Miao Miao. This project was recently displayed at the Materials & Applications site in Silver Lake. Bubbles “is an adaptable spatial pneumatic installation at an urban scale. The installation...[consists] of large pneumatic volumes that inflate and deflate in reaction to the visitors coming to the site.” The overall structure is thirty-seven feet tall, and incorporates a total of sixteen “bubbles,” or balloons that are eight feet in diameter. Half of the bubbles are located toward the ground, which allow for interaction with the people within the space. The other eight sacks are located above the lower ones; each lower bubble is paired up with an upper bubble. “Sensors in the bubbles cause a fan in the manifold to transfer air to the bubble directly above,”6 thus creating a path for movement through the rest of the space. When idle for a long period, “the lower bubble in the pair refills with air and awaits another interaction.” When a visitor enters the space, they must create a path throughout the installation. This is accomplished by hitting the first bubble, which causes the system to activate and begin altering the space according to the user’s preference. This interactive system glows

Figure 25 Bubbles interaction (http://www.interactivearchitecture.com/)
at night, creating a beautiful space that has the ability to completely define and re-define the space, making the experience of the space both entertaining and delightful.

9.2.10 META-MORPHIC ARCHITECTURE

This project was only tested on a small scale, and was never actually developed into an architectural-scale project, but the concept is certainly worthy of mention.

The idea is that these diminutive cubes could interact with one another and create a new configuration of a space at the user’s will. These cubes, about the size of a grape, have a brain of their own, and have the ability to pick up, move, and place each other in the desired locations. Any architectural component of a space can be configured of these cubes, including walls, ceilings, floors, and furniture. This system would allow for a complete alteration of a space, giving total flexibility in the configuration of the inhabited space. In a quick manner, the user could have the system rearrange furniture, divide and undivided areas, and adjust ceiling heights.
9.3 THE ENERGY SOURCES
Now as we have discussed briefly about all the major components of a building like structure, façade, lighting and energy in the previous chapters, we all know that we have smart materials to build a basic home. But let us start with a more complex environment like a community, which is described as a set of homes with other amenities for the population within the region. These communities further create a town or a city and the need for other amenities for the population. Thus for easy language we have a city as a Superset and the communities as the subsets of this superset. And the subsets have smaller subsets as homes and offices. Each set is housing an average defined number of humans.

9.3.1 THE HUMAN BODY AS AN ENERGY SOURCE
Human body is the home of many chemical processes and mechanical processes which are energy based. For every process in which the energy changes its form 40 percent of energy is wasted in the transformation which is liberated as heat energy. This heat energy dissipates from the human body to the environment. Also there are many other energies based on the emotional and mental state of a human. The human senses captures the intensity of these energies from the other humans and we further consider it as the positive and negative vibes of energy from the other person. At an average the energy which is coming out of the human body if can be tapped somehow then the amount of energy tapped in 1 hour through an emotionally stable person can harness electric energy to light a bulb of 100 watts for about 2-3 days.

The human emotion sensors also work through these energies. When a person feels sad, his heart rate decreases considerably and the body temperature is reduced, while if he gets angry
the body temperature is increased and the heart rate is also increased. This rate of increment and decrement is also specific for humans and other living beings. An emotion sensor detects this change in the human temperature and heart rate.

9.3.2 THE NATURAL FACTORS AS ENERGY SOURCES
At a time when the wind strikes on the window pane and the water drops fall on the rooftop the structure bears the dead load of these and transfers the weight to the ground. The energies are thus wasted in this procedure of transferring. The heat dissipated by these processes is lost in the environment.

In summers we have hot climate in most of the parts of the world. We use air conditioning and other cooling devices to overcome the heat of the environment. This process of using the cooling devices costs energy in a considerable amount.

The solar energy is also not used to the fullest in most of the parts of the world and the tidal energy is also not taken in consideration for the production of energy worldwide. The other renewable sources are geothermal, water streams etc. which can be used in big scales to generate energy.

9.3.3 THE INTERNAL AND EXTERNAL ENERGY OF THE BUILDING
The building which we have now can get the energy from the human body chemical processes and the natural factors. This in turn can specify the usage of the energy for different processes like air conditioning, lighting, movement and rotation of the building (this is to be specified later in the chapter) etc.
When taken in consideration we can divide the energy system into two categories. The first one called the internal building energy system which can take care of the energy requirement for the comfort of the inhabitants. This energy can be obtained by the human body, the human waste etc. The second one called the External energy system can meet its energy requirement by the natural and climatic factors like rain, wind, sun etc. This can help in the movement of the building and the rotation along an axis.

9.4 THE REGULATION CENTER – THE BRAIN OF THE BUILDING

The human body is like a building which has our bones as the structural members, the skin as the building facade and the inner organs together serving a living form called the brain. This brain interprets the outside world and gives the output in form of speech derived from thoughts. The modern buildings lack a brain which can interpret the world outside and transform the ideas into a speech which can be understood by the others. We can learn from the human body and try to join the new technologies with the architectural imagination to form a new type of building system which can sustain every climate condition and have the capability of intelligently responding to the environment.

The brain of a building can be a centralized computer system which can understand all the major climate changes and emotional changes of the living beings inhabiting the space. More or less this can be acquired by the use of actuators and sensors which can be incorporated in the structural system or the skin of the building. These sensors can act as the nervous system of the body and keep sending signals to the brain about the typical behavior of spaces in the building. The smart materials like optic fiber composites, smart composites and smart tagged composites can be used for building the nervous system. The electroluminescent materials,
phosphorescent materials can be used to get the signals of energy changes in a particular space, while the electrothermals can be used to diagnose the temperature difference in spaces and human bodies. This brain can get the energy from the energy sources which in turn harnesses the energy from the different factors mentioned before. This centralized system can be based on the network of the city.

9.5 THE STRUCTURAL SYSTEM
The buildings are designed to take the live load and the dead loads of the building and transfer them safely to the ground. They are designed to take over the horizontal and vertical loads due to various forces. The buildings in the present world are not flexible enough to transfer the forces so that they can be used wisely. And also they are not fully resistant to earthquake. For this we need a more flexible and reliable type of structural system. But is any system can be so flexible that it can overcome the forces of any major earthquake?

When at a building we have large gatherings and parties we need more spaces and when no one is there it can be smaller in size. And this thing also implies for a community or a housing too. So, can the system be so flexible that it can understand the space requirements and mould according to it?

In this modern era when the world is talking about carbon fibers and nanotechnology, it is not so hard to consider a very strong structural system. But to make the system flexible we want to add more to the structure as we have seen in the case studies above. We have to make the structure alive as I have mentioned it before in the Chapter 6. To overcome the structural vibrations and to make the structures “smart” we should compare it to the human body and
add muscles and tendons to it. It is hard to explain this phenomenon without any example, so let us assume a 2 mm thick wall with fibers of nanotubes or even carbon fibers. In these fibers we are adjusting the shape memory polymers and viscoelastic liquids that they can attain the desired shape according to the heat given to them and can be able to remember the first form accordingly. Piezoelectrics can thus generate the electrical impulses on a shape deformation and dielectric elastomers can remain in the shape you needed. Every time one just have to think about the situational gathering and the brain can adjust the spaces accordingly. It will send the walls the message to expand in a particular direction to fit in the set number of beds and chairs. As in a network the brain will know the space requirements for the family living next to you and similarly in a building it will know about the space requirements of the other families. This system is strong enough to bear the self weight, the inhabitant’s weight and the other forces. Also it is very flexible according to the inhabitant usage and it is light enough to be rotated and moved by any of the new technologies.

9.6 THE CONCEPTUAL BUILDING
We have talked about all the structural, lighting, façade, energy and the thinking systems of the conceptual building in the previous chapters. Now let’s analyze the ideal behavior of the conceptual building, its drawbacks and the inhabitant usage.

Considering the building to be self thinking and self changing, we will be having the following advantages:
• The building can sustain have zero energy usage from the outside world and it will be totally dependent on its own energy. This will further be helpful when the energy output is positive in case of public spaces.

• The building is flexible enough to sustain any natural forces and thus sustaining all the major disasters.

• The building can follow the wind and solar paths according to the inhabitant requirement and thus the power usage for many purposes like air conditioning and lighting can be lowered down by a considerable amount.

• The building can understand the inhabitant requirement and mould accordingly to provide optimum space.

• The building can optimize its energy usage. For example in case of working hours the building can provide enough light and at the time of no public the building can close down all the energy usage.

• The community spaces can also be provided with the energy resources from these sources.

• The building can understand the optimum human environment and provide a constant temperature for the human inhabitants.

• The building can clean itself on its own and the residual waste can be easily sorted out and used for other purposes.

• The building can understand the environment on the sub atomic level and respond accordingly with the chemical changes in the environment.

• The human labor thus can be reduced by a considerable amount.
- The building will perform on the optimum level in all the climatic conditions.
- The building can generate energy on its own in all the environmental conditions.
- The emotional changes in the human behavior can be understood in more depth easily and the building can follow the inhabitant accordingly.
- The natural environment is thus unaffected and unadulterated by human occupancy.
- The use of non-renewable energy sources can be lowered down in a considerable amount.

The drawbacks of the building are as follows:

- The building construction cost will be much more in the first period of construction which is not affordable by the majority.
- The social behavior of humans could get hampered living in such conditions.
- The material philosophy will be ever-changing and it will be dependent on the new products.
CHAPTER 10: ANALYSIS AND CONCLUSION
10.1 ANALYSIS
Smart architecture is an evolving field of architectural practice and research. This type of architectures is the one that measure actual environmental conditions (via sensors) to enable buildings to adapt their form, shape, color or character responsively (via actuators).

It aims to refine and extend the discipline of architecture by improving the energy performance of buildings with responsive technologies (sensors / control systems / actuators) while also producing buildings that reflect the technological and cultural conditions of our time.

Responsive architectures distinguish themselves from other forms of interactive design by incorporating intelligent and responsive technologies into the core elements of a building's fabric. For example: by incorporating responsive technologies into the structural systems of buildings architects have the ability to tie the shape of a building directly to its environment. This enables architects to reconsider the way they design and construct space while striving to advance the discipline rather than applying patchworks of intelligent technologies to an existing vision of "building".

The common introduction to responsive architecture is usually made by using the example of the thermostat. It is a basic example of a cybernetic feedback loop placed in a building environment in which the actual output is affected in response to an input. A sensor distributed in the environment is monitoring its change (as for example a decline of temperature). A controlling device, which may also enables a user to enter his/her preferences (a change in space temperature), is reading the sensory output and compares it to a predefined instruction (hold a certain space temperature). If there is a change in the input criteria (temperature dial) the controlling device is triggering actuators (the heating system) which are able to change the
environment. The thermostat is an example for what Don Ihde calls in his classification background phenomena. That is, as the term reveals, when a “specifically functioning technology” occupies a “background or field position” or becomes “a kind of near-technological environment itself.” Once set, these technologies, controlling for example lighting, heating, and cooling systems, are operating more or less automatically. They do not require our focal attention. These technologies in the background would be a source of conflict for a phenomenology, because they disconnect us from activities that bring change to an environment we live in. It is shown in a missing acceptance for the nature of technology and its development as a fact of human endeavor. Ever since technologies have been deployed and accepted, they, on one hand, intended to change our ways of doing and on the other hand they also have changed the production of environments and social fields where we place our doing.

While a considerable amount of time and effort has been spent on intelligent homes in recent years, the emphasis here has been mainly on developing computerized systems and electronics to adapt the interior of the building or its rooms to the needs of residents. Research in the area of responsive architecture has had far more to do with the building structure itself, its ability to adapt to changing weather conditions and to take account of light, heat and cold. This could theoretically be achieved by designing structures consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. Similarly, windows would respond to light, opening and closing to provide the best lighting and heating conditions inside the building.

The implications of Smart material technologies in the field of Architecture is based upon the usage and cost implication.
10.1.1 SMART MATERIAL VERSUS SMART TECHNOLOGY
In the first chapter with the introduction of smart materials and smart technology, we have discussed that these are the fundamentals of the future architecture across the world. But is Smart material related to Smart technology in any sense? Yes, it is, the former is related to the later in many ways. We can say that all the smart materials can create a smart technology and a smart technology can be using a smart material.

A smart material is not only used in building construction but the first usage of it was in the field of technology. Except this these materials are also used in the fields of information technology, automobile engineering, health and medicines, transport, aeronautical engineering etc. There is no doubt that these materials are the future of the building technology, but these are just the building blocks.

Smart technologies are not new in the field of architecture and they are not solely constructed out of smart technologies. These technologies are very old and ages from the era before the first brick walls were constructed. For example using a stone wall of 400 mm thickness in a hilly region is a smart technology, as these walls are the barrier for the cold weather to come inside the room and also are the barrier for the warmth to go out of the room. Similarly keeping the livestock in the ground floor, using air gaps on the roof etc. are considered to be smart technologies.

It is not at all important that all the smart buildings are made up of smart materials and all the smart materials create a smart building. It’s basically based upon the usage of these materials and their ability to respond to a stimulus.
10.1.2 LIFE CYCLE COSTING OF SMART MATERIAL TECHNOLOGIES

Life cycle cost (LCC) refers to the total cost associated with the deployment of Smart materials during their economic life. Total cost includes all costs incurred during the design, development, installation, operation, maintenance and disposal. Traditionally, the cost for operation, maintenance and disposal far exceed the installation costs. Life cycle costing based decision making, therefore, aims at choosing the most cost-effective product that optimizes the total cost of its deployment.

Most of the smart materials are not available in the market for usage. And the materials which are available have a very high cost index except a few. The cost index can be described as below:

- The Polymer and Electroluminescent materials are low cost which starts from US $ 1350 for per square feet.
- The Photochromic glasses are easily available and their cost depends upon the thickness of the glass. For square feet of glass with the thickness of 8 mm the cost will be starting from US $ 250.
- The cost of optical fibres is also very low and they are easily available in the market.
- The costing of a carbon fibre for industrial purpose start form US $ 7500 for per square meter with thickness of 4 mm.
- The costing of Kevlar starts from US $ 800.
- The thermochromes, photovoltaics, shape memory alloys etc. are not available in the market.
• A computer generated system to harness the energy from the peizoelectrics will cost around US $10000.

• A padded motion detector for 1 meter square area will cost around US $1200.

• Most of the smart materials are still in the process of designing by various scientific research institutes.

The material costing and the installation charges for these systems are too costly for even using them for research. But once installed these systems can work for a life cycle of 50-80 years depending upon the type of usage. Most of them are not recyclable and are not meant for more than one purpose of construction.

When we consider the equation of life cycle costing, it can be easily seen that they are more efficient than the normal building materials. The basic equation for determining the Life cycle costing will be:

\[ \text{LCC} = \text{Ca} + \text{Cp} + \text{Ci} + \text{Cm} + \text{Ct} + \text{Ce} + \text{Cs} \]

In this equation,

\( \text{Ca} = \) Acquisition cost (use and design)

\( \text{Cp} = \) Operation cost (equipments needed to calculate the operation process)

\( \text{Ci} = \) Installation cost (labour, material, equipments)

\( \text{Cm} = \) Maintenance cost (maintenance of the wear and tear of the material)

\( \text{Ct} = \) Down time cost (System reliability costing with the insurance)

\( \text{Ce} = \) Environmental impact cost (cost of environmental impact)

\( \text{Cs} = \) Disposal cost (disposal of non renewable materials after use)
10.1.3 ARCHITECTURAL USE AND FUTURE POSSIBILITIES
The development of true smart materials at the atomic scale is still some way off, although the enabling technologies are under development. These require novel aspects of nanotechnology (technologies associated with materials and processes at the nanometer scale and the newly developing science of shape chemistry.

Worldwide, considerable effort is being deployed to develop smart materials and structures. The technological benefits of such systems have begun to be identified and, demonstrators are under construction for a wide range of applications from space and aerospace, to civil engineering and domestic products. In many of these applications, the cost benefit analyses of such systems have yet to be fully demonstrated.

The Office of Science and Technology’s Foresight Programme has recognised these systems as a strategic technology for the future, having considerable potential for wealth creation through the development of hitherto unknown products, and performance enhancement of existing products in a broad range of industrial sectors.

The concept of engineering materials and structures which respond to their environment, including their human owners, is a somewhat alien concept. It is therefore not only important that the technological and financial implications of these materials and structures are addressed, but also issues associated with public understanding and acceptance.

Interactive architecture can be seen as an emerging multidisciplinary genre assigning new technologies a creative role that negotiates future identities for architecture relying not solely on a mechanical paradigm, but one that is supernatural and therefore not predetermined in
behaviour. Most of the first interactive architectural projects are based on mechanical principles of adaptation. A number of developments drawing on a range of technological and material means are beginning to adopt biologically inspired principles which lead to projects operates like organisms, analogous with the underlying design and processes of nature. A biological paradigm of interactive architecture requires not just pragmatic and performance based technological understandings, but a comprehension of aesthetic, conceptual and philosophical issues relating to humans and the global environment. Further, it repositions the role of the architect and designer as a catalyst of projects which evolve. The organic paradigm also reinterprets the scale at which architects and designers work and view the world, and also the timescales at which they customarily work. Interestingly, the issue of scale is inherently tied to manufacturing and fabrication. While recent innovations have been derived through electronics, we are beginning to see an accompanying upsurge of innovation in manufacturing and fabrication techniques appropriated from other industries and redeployed. Many early examples of interactive architecture have been based on rapid developments in digital media and its growing availability in terms of cost, but also on the creative reuse of existing electronic products. Their creativity largely depends on custom-designed software, rather than off-the-shelf products. The impact of new aspects of ubiquitous digital technologies, such as voice recognition, as with all innovations in this field, is exploited commercially as social media, but is also likely to be utilised by interactive practitioners.

10.2 CONCLUSION
It is important to explore the notion of interactive architecture and the concept of humans communicating with the built environment with the constant advancement in technologies that
affect our routines daily, which is exactly opposite of how architecture has been known. As the fields of electrical and mechanical engineering progress and the technology to fabricate more precisely and more rapidly are enhanced, the capability of implementing complex kinetic design into the built environment is certainly possible. These interactive systems have the capability of enhancing the spatial efficiency, security, transportability, aesthetics, and the overall experience of the built environment. Interactive design in architecture is able to diminish the communication barricade that is so dominate in our society today.

What we have achieved till date in the field of traditional and contemporary architecture is just the starting point of the human emotional involvement with the building he is living in. The narrowing down of distance between the human and the building mechanism can be the key to successfully advance towards a better lifestyle. The smart building concept can help the energy crisis of the modern era.

Interactive systems introduce a new approach to architectural design where objects are conventionally static, use is often singular, and responsive adaptability is typically unexplored. It is difficult to see if such architectural systems are far on the horizon or inevitably in the very near future. Adaptive response to change should intelligently moderate human activity and the environment and build upon the task of enhancing everyday activities by creating architecture that goes beyond “enhancing” our everyday activities to “extending” our capabilities. Interactive architectural systems introduce a new approach to architectural design where objects are conventionally static, use is often singular, and responsive adaptability is typically unexplored. Designing such systems is not inventing, but appreciating and marshalling the
technology that exists and making it to suit an architectural vision. To a great extent the success of creating such systems in architecture will be predicated upon the real-world test-bed. The result will be architecture of unique and wholly unexplored applications that address the dynamic, flexible and constantly changing activities of today and tomorrow.

The goal of such architecture lies in creating spaces and objects that can physically reconfigure themselves to meet changing needs with respect to changing individual, social and environmental needs and the dynamics of architectural space. Such systems today are inevitably in the very near future. The goals of such pioneering works are where the lasting relevance will be defined. It will be defined as technology unfolds as it is inextricably tied to living trends which they will ultimately and simultaneously both respond to, and define.
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