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A COMPILATION OF BIOLOGICAL LAWS, EFFECTS, AND PHENOMENA, WITH ASSOCIATED PHYSICAL ANALOGS

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AIR FORCE AVIONICS LABORATORY
ELECTRONIC TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
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Prepared under Contract No. AF 33(657)-7099 by
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FOREWORD

This is the final report on work performed under Contract AF 33(657)-7099 to compile a set of biological laws, effects and phenomena with associated physical analogs. The work was sponsored by the Bionics Branch of the Electronic Technology Division, U. S. Air Force, Wright-Patterson Air Force Base, Ohio. Task Scientist for the work was Dr. Mildred B. Mitchell of the Bionics Branch.

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ABSTRACT

A compilation of biological laws, effects and phenomena and their associated physical analogs is presented. Information on each law, effect or phenomenon is contained in separate entries which are grouped roughly into sections by similarity of content. Entries are cross referenced by animals and plants mentioned in each entry, by sample physical devices, systems, effects or phenomena analogous to the described biological law, effect or phenomenon in each entry, and by physical class (i.e., by the branch of physical science most relevant to the biological description) and by physical operator (i.e., by the categories of sensor, transformer, or actuator, whichever is more nearly descriptive of the entry).

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LIST OF ABBREVIATIONS

Å	Angstrom(s)
C	Centigrade
cm	centimeter(s)
cps	cycles per second
cu in	cubic inch(es)
db	decibel(s)
( )°	degree(s)
°C	degree(s) Centigrade
°F	degree(s) Fahrenheit
emf	electromotive force
ft	foot (feet)
g	gram(s)
kc	kilocycle(s)
kcs	kilocycles per second
m	meter(s)
mg	milligram(s)
min	minute(s)
/min	per minute
mL	millilambert(s)
ml	milliliter(s)
mm	millimeter(s)
mm^2	square millimeter(s)
mph	miles per hour
mmho	millimho(s)
μ	micron(s)
μg	microgram(s)
mμ	millimicron(s)
ms	millisecond(s)
mv	millivolt(s)
RC	resistive-capacitive
rpm	revolutions per minute
sec	second(s)
/sec	per second
v	volt(s)

INTRODUCTION

This report summarizes the results of a two-year effort to compile and describe the physical analogies of a selected list of biological laws, effects, and phenomena. The objective of the work is to provide engineers and physical scientists with a source of information and references on the properties of biological systems and the methods of "problem solving" employed by living systems. In addition, this compilation provides a series of case studies in bionics which examine the structure, function or behavior of organisms from both the life sciences and physical sciences points of view. In this sense, it is, therefore, also a contribution to methodology in bionics.

In view of the large quantity of available biological material, it was quite apparent from the outset that this study could not be carried to the point of exhausting available literature. A criterion for the selection of material was therefore needed to achieve a compilation of any coherence or utility. Relevancy of material to the problems of information and control was the primary criterion for the selection of material for inclusion in this compilation, but we have departed from this criterion a number of times in an exploratory spirit.

During the course of this study four principal types of problems were encountered:

(1) definition of terms

(2) classification of information

(3) accumulation and selection of material, and

(4) effective (and accurate) presentation of material.

The following discussion summarizes the approaches taken to these problems.

1. Analogy

Within the biological sciences homology and analogy have often been used as guiding principles. Since homologous structures are definable only for systems that are related through evolutionary development, it seems evident that bionics, concerned as it is with the relationships of living systems to

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physical systems, must be more concerned with the principle of analogy.

The term analogous is used in the biological sciences to denote the functional similarity of two structures. For example, the insect wing and the bird wing are analogous in function.

In the physical sciences, when one system is said to be an analog of another, it usually means that the same functional description applies to both systems. For example, a spring-mass-damper system and an R-L-C network can both be described by the same differential equation. Further, the components of one system are also said to be analogs of the elements of the other system: a mass is the analog of inductance, damping coefficient is the analog of resistance, spring constant is the analog of capacitance (or, rather, its inverse), force is the analog of electromotive force, and displacement is the analog of charge.

Although the usage of the term analog is somewhat more precise in the physical sciences, the intent of the term in the life sciences is quite similar. However, it is evident that we must adopt a broader definition of analog for use in bionics than is used in the physical sciences. For, in general, we cannot say that all the elements of a given physical system can be put into one-to-one correspondence with the elements of some living system, or that all the functions of a living system are performed by some analogous physical system. Living systems are far too complex and physical systems usually too simple for such a mapping to be established. We have concluded that it is reasonable to say that a physical system is the analog of some living system if a subset of the functions of the living system can be equated to the functions of the physical system.

Living systems are integrated wholes, however, and the question of degree of similarity and the level at which two systems are similar inevitably arises. To illustrate this point, consider the structures, functions, and behavior of bats using echo-location in the process of searching for food. Vibrating strings are analogs of the vocal cords used to produce the sounds emitted by bats, and the hollow chambers in the bat's skull act as resonating cavities to enhance the sound. A microphone is analogous to parts of the hearing organ, since both convert sound waves to signals. Since the returned signals are analyzed and used for guidance and control purposes, we can say that a guidance and control computer is the analog of this facet of the bat's make-up. The entire process of echo-location has the similar process using sonar or radar equipment as its analog. The activity of searching for food has no close analog, although the automatic reorientation of a satellite to obtain maximum sunlight on its solar cells might be considered a nontrivial analog. In the process of flying, the bat expends chemical energy, converting it into mechanical energy; hence, a gasoline engine is an analog of this part of the bat, although probably a rather poor or

superficial one. We can also aggregate functions and state that an airplane which is flying, converting stored energy into mechanical energy, using radar to detect other aircraft, and processing sensed information to produce guidance and control signals is an analog of a bat which is flying and using echo-location. Certainly there is very little structural similarity between a bat and an airplane, but there is no doubt that they have many functions in common.

On the basis of examples of the foregoing types, it would appear that what we would consider to be a physical analog of some living system depends greatly on the function of interest to us and that the degree of similarity between a physical system and a living system depends upon the context. Hence, a physical analog might be "good" with respect to one subset of functions of a living system and "trivial" or "poor" with respect to some larger class of functions.

Within this report quite a bit of latitude has been permitted in the usage of the term analog with respect to the degree of functional similarity and scope of the term. Ultimately, it is expected that workers in the field of bionics will settle on some interpretation of this term, and the present work can be considered as an exploration of some possibilities.

2 Laws, Effects, and Phenomena

In the sense that there are physical laws, there are probably no "biological laws"; in any event, the matter has been debated by experts at great lengths.

For purposes of this report, we have defined a biological law to be any observed regularity within a class or group of living organisms. Laws have one characteristic in common with effects: they usually relate measurable entities. The major distinction between laws and effects is that of their generality or extent. Closely related to laws are principles which tend to tie together the information from many different observations. However, not all principles can be proved. Even though principles frequently lead to correct predictions, they can be used only as an integral part of the formulation of a problem that would, in the final analysis, be solved by the application of known laws.

An effect is generally considered to be an immediate consequence or result of a given arrangement of entities and forces. A biological example is the response produced by the application of a stimulus to a given organ. In some cases it might be possible for an effect to involve two or more organisms in a synergistic relationship. There are many different kinds of known biological effects, and those associated with sense organs were selected as being of primary interest for this study.

A phenomenon is a singular occurrence of events or any given existing entity. The application of this definition to the biological field requires that the morphological characteristics of any given organism be considered as phenomena, although they are not usually classed as such and the term mechanism might be more appropriate. Examples of these are the compound eye, wings, fins, infrared sensors, and other animal organs. Although these structures may have resulted from a series of evolutionary forces, they would be considered phenomena in contrast to effects since their appearance was not an immediate consequence of these forces.

3. Organization of the Compilation

Material on each law, effect or phenomenon has been collected into entries. As we noted in the discussion on analogy, the type of analogy and the descriptive material depend on the scale of events and the possible objective of the user of the information. Most entries are confined to a limited aspect of a functioning organism although titles for the entries have been picked largely to convey the general nature of the material.

Entries have been grouped by sections; the section titles should be considered more as descriptive of the entries within the section rather than as classifications.

In view of the numerous possible uses of this compilation, five cross references for the material have been provided. These cross references should enable the reader to find material of interest by the organism, plant or animal, by the branch of physical science most closely related to the material (the physical class) by the operations or functions performed (the physical operator), and by the type of physical analog most closely related to the law, effect or phenomenon. Information concerning Physical Class, Physical Operator and Section is indicated at the top of the first page of each entry.

a. Entries

The entries contain material divided usually into six groupings: description, illustration, magnitude, similar examples, sample physical analogs, and references. In some entries, the description and illustration or illustration and magnitude have been combined. In other entries one or more of the groupings of information may be missing, either because the material was inappropriate or could not be found. Sample physical analogs are missing from a number of entries in the last three sections, Special Laws, Special Effects, and Special Phenomena, usually because the analogs for these entries are trivial or else do not exist. The biological information in the entries without physical analogs could be of interest for

no other reason than the fact that physical analogs do not exist, or, at least, are not readily apparent.

b. Sections

Entries have been grouped into sections on the basis of general similarity and as a means for better access of material. As mentioned, the section titles are more descriptive than classificatory. For example, the term sensitivity in the sections Thermal Sensitivity and Chemical Sensitivity can be interpreted two different ways on the basis of included material. Some biological effects of heat are due to changes in system parameters, such as metabolic rate, while other effects of heat include the signals produced by thermoreceptors and the behavioral or functional changes induced by the signals of heat. The latter two types of changes could be of interest for information processing systems, while system parameter changes are more nearly materials properties. Similarly, the Chemical Sensitivity section includes entries on both sensitivity to chemicals and the detection of chemicals by specialized sensors. Although these sections could have been split into two parts, similar comments could be made about other sections, and the choice of aggregation was made in part due to the small number of entries in these sections. As a further example, the section Electrical Energy contains information on both the detection of electrical energy and the generation or production of electrical energy, even though sensitivity and production are treated in separate sections for other types of energy.

c. Cross References

There are five cross reference sections in the compilation:

Cross References by Physical Class lists each entry under the physical class which pertains to it.

Cross References by Physical Operator is divided into cross references by Actuators, Sensors, and Transformers.

Cross References by Physical Analog includes all sample physical analogs named in the entries, listing all entries in which each appears.

Cross References by Animal provides a listing, by animal, of all entries in which the animal is named. Listings are provided for such categories as "MAMMALS IN GENERAL", "VERTEBRATES IN GENERAL", etc. When a class of animals, such as fish, has references to many different species and types, a special

listing appears below the main list, e.g., "FISH IN GENERAL..." "Species and Types of Fish:...". Some phyla, genera or species are cross-referenced to more familiar names, e.g., "PETROMYZONS, See: LAMPREYS".

The Cross References by Plant follow the same general guidelines as the Cross References by Animal.

d. References and Related Literature

The reference material which has been used in this compilation has been divided into two categories: "References" and "Related Literature". The section "References" includes all the reference material which has directly provided the material for the articles themselves. These are arranged alphabetically by author and have been numbered consecutively. The appropriate number(s) and the relevant pages appear at the end of the entry to which they pertain.

The second reference section includes any additional sources which, although not directly cited in the specific articles, are nevertheless closely related to them in subject matter. These are arranged alphabetically according to the sections to which they are related.

The references have been organized in the following manner: books and articles (magazines, journals, etc.) are listed alphabetically by the author's last name; if a group of independent articles has been gathered into one book, each article referred to is listed under its own author's name.

4. Orthography and Abbreviations

Most of the spellings of biological and technical or scientific terms were verified in Webster's New International Dictionary of the English Language, Second Edition, Unabridged, 1959. In the event of disagreement between this dictionary and the scientific reference books, other authority was consulted, such as the Entomological Society of America. Some verifications were obtained from the Microbiology Department of the George Washington University and the National Geographic Society.

Three principal sources were consulted for abbreviations: The United States Air Force Dictionary, Webster's New International Dictionary of the English Language (Second Edition, Unabridged), and Sams' Modern Dictionary of Electronics.

SECTIONS OF THE COMPILATION

SECTION 1:

BEHAVIOR

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BIOLOGICAL ASPECTS OF BEHAVIOR

Behavior is the manner in which animals conduct themselves; in other words, what they do, when they do it, and why. A great amount of work has been done on the study of animal behavior. Most of these studies probe the question of behavior from one of two approacnes. One is the individualistic approach. Experimentation, especially training criteria, has established the reaction of many animals to various qualities and quantities of light, odor, taste, sound, touch, and other stimuli. The reaction and adjustments of an individual to abnormal situations have resulted in information on learning ability and the orbit in which instinct and intelligence overlap.

The second approach deals with the behavior characteristics of the species. The entire life cycle of an organism is a succession of definite behavior patterns. Even in the same species they change constantly and regularly.

The basic units of inherited behavior are reflex actions, that is, automatic responses to the same stimulus. When the entire organism orients itself automatically in relation to a given stimulus, this is known as tropism. For instance, at night certain species of moths will always fly towards a flame, exhibiting a positive tropic response to light. Tropisms which are inherited and therefore operate without benefit of experience are called instincts. Insect behavior in general is predominately instinctive, but it is not a simple addition of reflexes, tropisms, and instincts. In the first place, these may be modified, inhibited, or coordinated as a result of experience or learning. In the second place, many investigators believe that the entire perceptual panorama of the organism forms a sort of pattern and that the organism responds to general changes in this pattern and not to the individual stimuli of which the pattern is composed.

PHYSICAL ANALOGS IN GENERAL

The study of behavior in living systems is the counterpart to essentially all branches of the physical sciences. The methods of study in the physical sciences differ from those used in the behavioral sciences in two key respects:

(1) It is sometimes possible for an experimenter to interact with a physical system to the point of significantly modifying the given physical system; although the behavioral scientist can also interact with living systems, he cannot do so to the extent of destroying the structural integrity of the system.

(2) The physical scientist is often concerned with the problem of synthesizing a system with desired properties and, in the process, he may modify parameters to obtain additional information about the system; the complexity of living systems is so great that most attempts at synthesis of living systems are or have been limited to trivial characteristics of the systems.

Since the simulacra of living systems are usually trivial, so also, are most other physical analogs, man-made or natural. However, physical systems designed to be analyzed by man have been steadily increasing in complexity. Such diverse systems as the DEW line, computers, pattern recognition machines, and learning machines now begin to rival in complexity and information processing capability the living system.

From the physical point of view, many aspects of behavior specific to a given animal must be treated as an accident of circumstance, a result of the interplay of the animal with its own environment, and generally not something that would necessarily be useful to duplicate. However, it is from the changes in overt behavior induced by injected chemicals, changes in illumination or temperature levels, or other factors that we deduce many of the properties and mechanisms of living tissues.

Physical Class	Physical Operator	Section 1
Chemistry Materials Properties Mechanics	Sensors Contact Internal Transformers Information Actuators Internal	Behavior

INFLUENCE OF HORMONES ON FIGHTING

DESCRIPTION:

An attack by one member of a species on another of its kind provokes fighting. In the males of many species, the male hormone, testosterone, is a significant factor in the regulation of fighting. Testosterone apparently lowers the pain threshold and, thus, increases the irritability of the animals.

ILLUSTRATION:

Experimental investigations with mice have shown that male mice fight quite frequently. When the males were castrated their source of testosterone was essentially removed. After recuperation groups of these males were placed in the same cages and did not seem to have the desire to fight. The implantation of testosterone propionate pellets in these males caused them to fight with each other as they had done before surgery. When the pellets were removed most of them stopped fighting, although some continued.

MAGNITUDE:

The hormone testosterone is the most active member of the natural androgens. An injection of less than 5 mg is sufficient to produce fighting in mice.

SIMILAR EXAMPLES:

Alcohols and their derivatives also affect the pain threshold of man. They produce a feeling of confidence and power dominance; they raise the threshold of pain and depress the action of the central nervous system.

REFERENCES: 132, pp. 86-87.

Physical Class	Physical Operator	Section 1
Chemistry	Sensors Actuators Internal Internal Transformers Energy Information	Behavior

INGESTIVE BEHAVIOR IN ANIMALS

DESCRIPTION:

Ingestive behavior may be defined as the actions of an individual which are concerned with the vital process of food consumption. This type of behavior may be divided into two major stages: (1) initial stimulation, which would include the search for food, and (2) ingestion, or the actual process of eating.

ILLUSTRATION:

Initial stimulation in humans includes contractions of muscles in the wall of the stomach producing the condition known as "hunger pangs". This feeling arises most frequently in humans just prior to the usual meal times. The frequency of initial stimulation appears more frequently in lower mammals than in humans and usually coincides with the degree of depletion of the blood sugar level, resulting in an increase of action. In rabbits and rats, initial stimulation was produced experimentally by allowing these animals to exercise extensively, thereby using up stored energy in the form of blood sugar. After the rats and rabbits were fed, the blood sugar level rose and activity subsided.

Ingestion of food in characteristic manner is exhibited more frequently and to a greater extent in lower forms of animal life. In the sea anemone Metridium, for example, the tentacles will continue to push food through the oral disc and mouth into the body cavity until the latter is completely full.

A less extensive ingestive reaction is demonstrated by the fresh-water hydra, which, after being fed a relatively small amount of food, does not seem to react to the presence of additional stimulation.

Insects are frequently classified into four groups on the basis of their feeding habits: vegetarians, predators, scavengers, and parasites.

Vegetarians feed on plants; for example, the larvae of the lepidopterous species feed on plants characteristic of the species. Predators, such as dung beetles and sarcophagid flies, live on captured animal tissue or derivative materials of plants or animals. Scavengers, such as scavenger beetles (Hydrophilidae), feed on refuse, carrion or other decaying substances. Parasites feed more or less fixedly upon the tissue of a "host" organism.

MAGNITUDE:

Ingestive behavior is a characteristic of all animal life; however, the extent to which it is visibly exhibited varies greatly. Among the lower animals ingestive behavior appears to

INGESTIVE BEHAVIOR IN ANIMALS, Continued:

make up a major portion of the individual's activities. As animal development progresses and social factors begin to influence animal life, ingestive behavior, although still an important factor, appears with more controlled regularity.

SIMILAR EXAMPLES:

The development of sexual behavior within the animal kingdom closely parallels that of ingestive behavior.

REFERENCES: 119, pp. 693-695; 132, pp. 685-722; 133, pp. 127-128.

Physical Class	Physical Operator	Section 1
Electricity and Magnetism Mechanics	Sensors Contact Distance Internal Transformers Energy Information Actuators External Internal	Behavior

INSTINCT AND INSECT BEHAVIOR

DESCRIPTION:

Insect behavior, i.e., the response to one or more stimuli, is governed, in most cases, by instinct. Since instinctive acts are usually performed without previous experience, they are not connected with reasoning. Essentially, they consist of groups of coordinated reflexes which in the case of insects may come from either external or internal stimuli as definite response patterns. Instinctive acts are usually repeated in regular rhythmic sequence, and may appear unchanged in numerous generations.

ILLUSTRATION:

A digger wasp will burrow a hole, bury another insect in it, and then lay an egg inside the buried insect. The wasp then puts other captured insects into the hole as food for the larva that will develop from the egg. With this series of events, the wasp completes the cycle of its instinctive act in a definite and unalterable sequence.

Even if the egg is removed from the immobilized captive before the wasp brings other insects as food, the wasp will continue to put food into the hole and then seal it shut.

SIMILAR EXAMPLES:

A moth caterpillar will invariably complete the spinning of its cocoon without stopping as long as it is left alone. However, if the caterpillar is disturbed, for instance by being picked up, the spinning process will stop. When the caterpillar is put down it will resume its spinning activities from the point where it stopped, completing the cocoon previously begun rather than starting a new one.

REFERENCES: 36; 119, pp. 669-673.

SECTION 2:

CHEMICAL PRODUCTION

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BIOLOGICAL ASPECTS OF CHEMICAL PRODUCTION

The living cell is a highly complex "chemical factory". Man has not constructed a chemical plant to rival the living cell in terms of the number and complexity of compounds produced. The fundamental substance of the cell has remained in its innermost essence undiscovered, although careful and extensive studies have been devoted to the mass of cell products.

The production of complex chemical compounds from simpler compounds by living cells is handled on a molecule by molecule basis. For example, the synthesis of protein is accomplished through the molecule interchange of amino acids. The actual protein synthesis within the cell takes place at the polysomes, where amino acids are added one at a time to form a long-chain protein molecule. Many such polysomes exist within a single cell and their total output therefore becomes appreciable.

Specialization of cells in multicellular organisms has led to glands or organs whose function is specifically the production of special chemicals. These specialized organs may produce chemicals for internal regulation of the activities of the body (such as that produced by endocrine glands), or for the elimination of waste (see, for example, "Salt Glands in Marine Birds"). Often, however, animals utilize chemical glands in coping with their environment. The sting of bees and some arachnids, the venom of snakes, the odor of skunks, the spider's web, and the silk of the silkworm are all familiar examples of the chemical means employed by animals. Most of the entries described in this section are of specialized organs for the production of chemicals used to cope with the environment.

PHYSICAL ANALOGS IN GENERAL

Chemical production by specialized organs in animals sometimes involves familiar principles of chemistry. For example, in the production of silk, (see entry on "Silk Production"), the Bombyx mori secretes thin threads of a saliva-like liquid from its oral glands or spinnerets. Due to mechanical stress in spinning, this liquid forms very soft threads of silk with a high tensile strength.

The production of artificial silk by the chemist involves a similar operation. Cotton is treated with an ammoniacal solution of copper hydroxide, and this solution is forced through a capillary tube into an acid solution which precipitates the cellulose as a long continuous fiber of silk.

By comparison with the techniques used in living cells, the techniques used by the chemist for the processing of chemicals always involves (relatively speaking) large quantities of raw materials in mass reactions. At this time there are no techniques for building up long-chain molecules by adding individual molecules at some specially prepared site of synthesis.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics Mechanics	Actuators External	Chemical Production

ASSASSIN BUG DIGESTIVE VENOM

DESCRIPTION:

The Reduviidae compriae, or assassin bugs, within the Order Insecta, inject a lethal venom into their victims, usually other insects. This venom "digests" and liquefies the surrounding tissue, permitting the assassin bugs to suck it up as food. The specialized organs associated with this process are located on the head, thorax, and forepart of the body. The salivary glands in the assassin's thorax produce and store the venom; pumps in the head force the venom through the beak into the prey, and also suck in the liquefied tissue. The jaws of the assassin bug are modified into two outer, or mandibular, stylets, which have barbed tips and flank two inner, or maxillary, stylets. The latter move in and out between the mandibular ones, each having two longitudinal grooves on their inner surface. They are faced together in register so that the complementary pairs of grooves form two tubular channels functioning as a "two-way hypodermic needle."

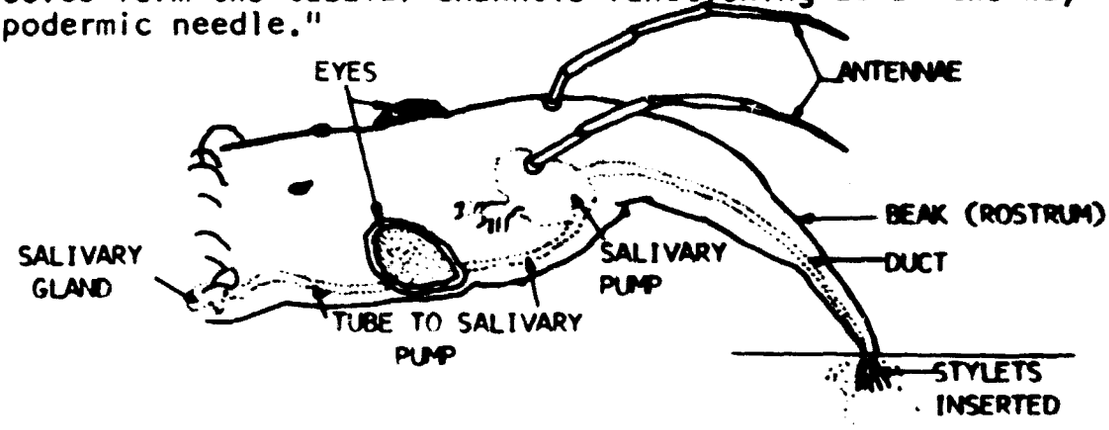

FIG. 1 HEAD OF ASSASSIN BUG SHOWING VENOM ROUTE

ILLUSTRATION:

The assassin bug grasps its prey with its legs and places its beak against the captive's body. Stimulated by action of retractor muscles, the "hypodermic needle" sucks saliva from the salivary glands through the flap valve on the thorax up to the beak. When the muscles are relaxed, the "hypodermic" springs forward, forcing a jet of saliva through the outlet duct in the upper wall of the pump, down the salivary canal of the stylets into the prey. After a short waiting period, the assassin bug feeds on the digested tissue by sucking the liquid back up through the stylets.

ASSASSIN BUG DIGESTIVE VENOM, Continued:

MAGNITUDE:

In laboratory experiments the assassin bug, Platymeris, was allowed to attack a cockroach, which died within 10 seconds. It was estimated that, during this period, the assassin bug was able to inject a minimum of 10 mg of saliva into the roach.

SIMILAR EXAMPLES:

Mosquito bites, bee and scorpion stings, and bites of poisonous reptiles are related. The injection of a killing, paralyzing or pre-digesting substance into another animal by means of a sharp hollow tube or detachable appendage may: (1) serve for defense, (2) prepare a live but paralyzed host (preserved meat) for larvae, or (3), assist in obtaining food for the animal injecting the poisonous substance. Mud wasps paralyze adult cicadas which serve as food for larvae. Aquatic life forms often possess stinging organs. Allied organs inject eggs in host animals or plants. Spiders and mosquitoes have sucking organs comparable to those of the assassin bug.

SAMPLE PHYSICAL ANALOGS:

Poison arrowheads or spear points, hypodermic needles, meat tenderizers, insecticides, and food preservatives are each analogous to some facet of the structures or compounds in the assassin bug.

Wells are often dug (jetted) by using apparatus very similar in action but different in intent. Water is forced under pressure through a pipe into a hole. As emission takes place the mud created is returned through another pipe to the surface. In this manner, the earth to be removed is first dissolved in a solution, then pumped to the surface of the hole, separated from the solvent, and the solvent (water) is reused. As the well is deepened, the pipes are lowered and the process is continued until the desired depth is reached.

Sulphur and other minerals are sometimes mined in a similar manner. In such cases the purpose is to retrieve, from the solution, the mineral that is desired. For mining sulphur, the solvent is hot water.

REFERENCES: 27, pp. 72-78.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics Mechanics	Actuators External	Chemical Production

BEE STING

DESCRIPTION:

The bee's sting is generally transitory and not usually serious, although it has been known to cause acute swelling and inflammation and rarely death. The sting mechanism consists of a sharp lance-like organ located at the posterior end of the body, a "poison" gland secreting formic acid, and reservoir system which empties to the outside through the lance-like organ.

ILLUSTRATION:

Before the bee stings, a suitable place is selected with the help of the sting feelers. The two barbed darts are thrust forward piercing the skin allowing the poison to be injected under the skin.

When a worker bee stings a victim, it usually leaves the sting and often a portion of its abdomen in the skin. When more than the sting is left, the bee dies. The parts of the bee sting are modified ovipositors and some authorities believe they represent abdominal appendages.

MAGNITUDE:

In the honeybee, the sting proper consists of two sharp, polished, brown spears or darts which appear as one. Each of the two darts of the honey bee's sting has 9 or 10 curved hooks or barbs near the end. As the insect stings, these two darts are very rapidly thrust into its victim to a depth of 1/10 of an inch, and occasionally further with subsequent thrusts. The small curved hooks prevent the bee from removing the sting.

SIMILAR EXAMPLES:

In scorpions the sting is found on the end of the tail, and is not used unless the scorpion is being attacked.

In the phylum Coelenterata most species have stinging cells called nematocysts which are used as organs of defense and offense.

SAMPLE PHYSICAL ANALOGS:

The functional aspects of the bee sting are modeled by a hypodermic syringe and needle in that injection of chemicals below the skin is achieved by both.

REFERENCES: 36, p. 57; 58, p. 278; 102, p. 298.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics Mechanics	Sensors Contact Actuators External	Chemical Production

DEFENSIVE SECRETIONS OF THE MILLEPEDE

DESCRIPTION:

Certain species of millepedes, when disturbed, emit a highly persistent, aromatic secretion, which is believed to be defensive in function. This secretion contains mostly benzaldehyde, C_6H_5CHO, and hydrogen cyanide, HCN, the latter compound being stored in its stable form called mandelonitrile.

ILLUSTRATION:

The cyanogenic secretion of the polydesmoid millepede, Apheloria corrugata, is discharged from paired, serially arranged glands, each consisting of two compartments. One compartment stores an undissociated cyanogenic compound, and the other a chemical factor that triggers cyanogenesis. The gland is constructed so the contents of the two compartments are mixed and cyanogenesis is initiated at the instant of discharge.

The secretion is ejected through small openings on the dorsal surface near the tip of some of the paired notal projections which are present on all body segments. Secretory ducts are located on segments 5, 7, 9, 10, 12, 13, 15, 16, 17, 18, and 19 in both adult males and females. The discharge usually occurs in response to traumatic stimuli only from the segments which are stimulated. When the millepede becomes highly irritated all the segments secrete.

MAGNITUDE:

The release of the cyanide compound by millepedes is gradual, rather than a rapid expulsion at the moment of stimulation. Quantitatively, 92% of the secretion is the benzaldehyde. The HCN, stored as mandelonitrile, forms approximately 2% of the remainder of the secretion. Carbohydrates are also found in small quantities.

SIMILAR EXAMPLES:

The secretion and ejection of para-benzoquinone compounds by the cockroach parallels in many respects the millepede secretions.

The irritating discharge from the poisonous hairs of nettling insects is similar in anatomical aspects and mode of discharge.

The sting of the whip scorpion also resembles the millepede secretions in discharge and effect.

SAMPLE PHYSICAL ANALOGS:

Poisonous and irritating gases used in warfare are analogous to the secretions described.

DEFENSIVE SECRETIONS OF THE MILLEPEDE, Continued:

Pilots and sailors are issued a special soap-like compound designed to repel sharks as it slowly dissolves in the water. This compound has a purely defensive purpose analogous to the secretions of the millepede.

REFERENCES: 10, p. 512; 40, pp 437-450.

Physical Class	Physical Operator	Section 2
Fluid Mechanics	Transformers Matter Actuators Internal	Chemical Production

LACHRYMAL GLANDS

DESCRIPTION:

Lachrymal glands produce a watery secretion which provides an amount of moisture to the surface of the eye and to the nasal passages. They are located in the nasal passage with ducts opening at the inner angle of the eyes which drain into the nasal chambers.

ILLUSTRATION:

The glands are innervated by parasympathetic secretory and vasodilator fibers which arise in a nucleus of small motor cells situated in the pons near the upper salivary nucleus. Parasympathomimetic drugs such as pilocarpine, muscarine, and acetylcholine stimulate lachrymal gland secretion, whereas parasympatholytic drugs, such as atropine, inhibit secretion.

MAGNITUDE:

The normal lachrymal secretion is 13 drops every 16 hours, of which 7 drops evaporate and the remainder flow into the nasal cavities. Irritation of the conjunctiva or the nasal mucosa increases lachrymal secretion. The afferent fibers of this reflex form part of the trigeminal nerve. Vomiting, sneezing, and coughing are accompanied by increased lachrymal secretion.

SIMILAR EXAMPLES:

The salivary glands, resembling the lachrymal glands in structure and general appearance, communicate with the mouth.

SAMPLE PHYSICAL ANALOGS:

The lubricating system in an automobile engine and the window washing devices of automobiles provide washing or lubricating functions analogous to those of the lachrymal glands.

REFERENCES: 7, pp. 1314-1315; 44, p. 1121.

Physical Class	Physical Operator	Section 2
Chemistry Heat and Thermodynamics Optics and Light	Transformers Energy Matter	Chemical Production

PHOTOSYNTHESIS

DESCRIPTION:

Photosynthesis is the chemical process by which plants containing the pigment chlorophyll absorb light energy and utilize it in converting atmospheric carbon dioxide to various carbohydrates. It is the process basic to formation of all the organic compounds of plants, such as proteins, fats, acids, alkaloids, and vitamins, as well as carbohydrates.

ILLUSTRATION:

The photosynthetic process is composed essentially of two general processes. In the first process, called "light reaction", the absorption of light by the chlorophyll system provides energy in the form of activated chemical compounds. In the second process, carbon dioxide is reduced by the active molecules formed in the light reactions, producing carbohydrates and other substances. The longest wave lengths of visible light are the effective ones in promoting photosynthesis. Infrared light (800-850 mμ) has also been found effective. The photosynthetic reaction may be summarized as follows:

$$6CO_2 + 6H_2O \xrightarrow[\text{(690 kcal of light energy)}]{} C_6H_{12}O_6 + 6O_2$$

MAGNITUDE:

The conversion of 6 moles of CO_2 to 1 mole of glucose requires approximately 690 kilocalories of energy, which is obtained from the radiant energy of visible light (4,000 to 7,000 Å) absorbed by chlorophyll.

SAMPLE PHYSICAL ANALOGS:

The solar cells (silicon, germanium, etc.) absorb light and convert it to electric power. There are other similar devices which generate electric power from the heat produced by light energy. One of these involves a cyclic variation in a charged capacitor. As the capacitance is changed in a direction in opposition to the electrostatic force, the heat energy is converted to electrical energy. The same principle can be applied using the cyclic permeability change of an inductive element to obtain electrical power.

No commercial use is made of sunlight as an energy source in chemical reactions.

Biological fuel cells and closed loop life systems have been devised by placing biological organisms in an artifical

PHOTOSYNTHESIS, Continued:

environment. These are not true analogs, but are examples of systems integrating the biological and physical.

REFERENCES: 12, pp. 439-452; 45, p. 767; 147, pp. 1000-1003.

Physical Class	Physical Operator	Section 2
Chemistry Mechanics	Actuators External	Chemical Production

POISONOUS HAIRS OF NETTLING INSECTS

DESCRIPTION:

The larva or caterpillar stage of certain moths, such as the saddleback moth and the flannel moth, have two types of hairs growing in tufts around the ridges of their numerous segments. The longer hairs are relatively harmless, and probably serve a partially sensory function of a tactile nature. The shorter ones, called the nettling hairs or spines, have tiny barbs at their tips and are attached to small glands just below the skin of each tuft which exude an irritating liquid. This gives the larva a highly effective protective device.

ILLUSTRATION:

When disturbed by touching, the underlying hypodermal "poison" glands, which have received stimuli from the outer area, contract rapidly and send out the irritating liquid through the hairs. Occasionally, these nettling hairs have been found on the corneas of the eyes of different animals, their "poison" secretion producing severe irritation.

MAGNITUDE:

This "poison" has been known to cause severe swelling of the general area around the point of injection, accompanied by intense and long-lasting itching sensation. Extreme intestinal disturbances have also resulted from accidental injections. Although its exact composition is not well-known, it is considered by many investigators to be more severe than the poison of a common bee sting.

SIMILAR EXAMPLES:

The bristles of the nettle plant are similar to the poisonous hairs of insects in that they contain a watery juice which, when it makes contact with the skin, produces an intense itching reaction.

SAMPLE PHYSICAL ANALOGS:

Poison tipped arrows and spears have been reportedly used to increase the lethality of these weapons.

REFERENCES: 36, p. 58; 102, pp. 21-22.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics	Sensors Transformers Internal Matter	Chemical Production

SALT GLANDS IN MARINE BIRDS

DESCRIPTION:

All marine birds have a salt-eliminating gland which can dispose of salt more effectively than kidney action. These glands, located on top of the skull above the eyes, consist of many lobes made up of several thousand branching tubules radiating from a central duct. The tubules, approximately one thousandth of an inch in diameter, secrete a solution of sodium chloride with a concentration of up to 5 per cent.

ILLUSTRATION:

When marine birds ingest food with a high salt content or drink sea water, the excess salt flows through the salt-gland duct into the nasal cavity, dripping off the tip of the beak. A network of capillaries carries the blood in an opposite direction but parallel to the flow of salt solution in the tubules. This functioning of the principle of counter-current flow amplifies the osmotic transfer of salt from the blood in the capillaries to the fluid in the tubules. A major difference between the human kidney and salt glands is that the latter function intermittently in direct response to concentration of salt and the need to eliminate it. The kidney secretes continuously at a varying rate.

MAGNITUDE:

A sea gull used in a laboratory experiment was given 134 cubic centimeters of sea water, which was equal to one-tenth of the gull's body weight. Within three hours the gull had excreted 90 per cent of the salt, the salt glands having produced approximately two-thirds as much fluid as its kidneys during this time.

SIMILAR EXAMPLES:

The loggerhead turtle has a similar salt-gland structure which is essential for the elaboration of fluids with a high salt concentration.

SAMPLE PHYSICAL ANALOGS:

Although machines devised to purify sea water are analogous in their function, they do not use the osmotic principle. Such machines usually depend on evaporation-condensation principles, or salt and other compounds are precipitated out of the solution by centrifugal force.

Osmosis can be demonstrated as a method of reducing the concentration of a solution by placing a piece of animal membrane in contact with a sugar solution. In osmosis, the passage of water molecules occurs but the larger, more complex sugar molecules do not pass through the membrane.

SALT GLANDS IN MARINE BIRDS, Continued:

The principle of osmosis has been demonstrated using inorganic materials by devising a semipermeable membrane using a thin film of copper ferrocyanide, $Cu_3Fe(CN)_6$.

REFERENCES: 129, pp. 65-66; 130, pp. 109-116.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics Mechanics	Transformers Matter Actuators External	Chemical Production

SILK PRODUCTION

DESCRIPTION:

Silk is produced by a variety of species and by diverse organs. The larva of the moth, Bombyx mori, produces a silk, which is a saliva-like secretion, exuded in thin threads from the oral glands.

ILLUSTRATION:

In the larva of the Bombyx mori the components of silk are found in the reservoir of the silk gland as a reasonably homogeneous colloidal solution which is soluble in hot water, 5-20% sodium chloride, and 5-10% sodium carbonate. The components are non-dialysable and are not coagulated by heat.

At the time of spinning, natural solidification occurs virtually instantaneously, with the formation of a highly crystalline central fiber (silk fibroin) surrounded by an amorphous coat of silk gelatine (sericine). The solidification of the fibroin that occurs at the instant of spinning is not due to exposure to air or to drying (since it can occur under water) but is probably due to the operation of stresses and shearing forces, which act to distort and perhaps to activate the molecular chains to give the steric configuration necessary for formation of the fiber. The process may be visualized as the aggregation of fibroin units into fibers under the mechanical influence of spinning, whereas the other components which do not fit into the fibroin lattice accumulate at the periphery to become the sericine portion of the raw silk.

The silk fibroin produced by the Bombyx mori is characterized chemically by its high content of glycine, alanine, and tyrosine. It is a simple protein filament giving the diffraction pattern of a fully extended polypeptide chain composed principally of alternating glycine and alanine units and having a side chain of relatively little significance. Estimates of the molecular size of silk fibroin vary from 40 to 2592 amino acid units per molecule.

MAGNITUDE:

The silkworms are able to produce silk at the rate of about six inches/min; this results in the formation of a complete cocoon in three days by a single strand approximately 1,000 feet long.

SIMILAR EXAMPLES:

A spider produces the strands for its web in a similar manner, but the strands are secreted from the spinnerets at the posterior end of the spider's abdominal body region. The

SILK PRODUCTION, Continued:

spider's silk-like strands are also strong, and have a coating of sticky material.

SAMPLE PHYSICAL ANALOGS:

The production of artificial fibers is analogous to the fiber production by insects, although few, if any, artificial fibers are hardened by tension or shear forces.

REFERENCES: 102, p. 46; 107, p. 14; 118, pp. 30-31.

Physical Class	Physical Operator	Section 2
Chemistry Fluid Mechanics Mechanics	Actuators External	Chemical Production

SPINNERETS IN THE SPIDER

DESCRIPTION:

In the spider there are three pairs of organs called spinnerets (web weaving organs), located just below the spider's anal opening, through which hundreds of microscopic tubes pass. The abdominal "silk" glands secrete a fluid which passes through these and hardens on the outside, forming a thread. These threads are used to build nests, cocoons, and webs.

ILLUSTRATION:

As a spider begins to spin a thread, it forces out the liquid silk by pressing the spinnerets against an object. As the spider moves away, the sticky liquid is drawn out and it hardens in the air. The spider can make one thick thread by keeping the spinnerets together or a fine thread by holding them apart. The large black and yellow garden spider, Eperia gemma, attaches its strands to the branches of a tree or a tall plant. This animal uses one of its hind legs to draw the silk from the spinnerets until a sticky thread floats through the air. When the thread sticks to another object a few feet or yards away, the spider fastens the thread end still attached to its body to the object, then crosses back and forth adding silk until it is strong enough to hold up the web. Next the spider starts a second thread and drops itself as it spins silk out from the spinnerets, fastening this thread to another object below. The spider then climbs up the thread to the main strand, and attaches other threads radiating out like the spokes of a wheel.

MAGNITUDE:

Spiders spin seven different kinds of silk and one individual spider can spin five different kinds.

SIMILAR EXAMPLES:

The secretion of the silk moth Bombyx mori is similar. This silk is a liquid, somewhat similar to saliva, that solidifies to a soft thread due to stresses in spinning.

SAMPLE PHYSICAL ANALOGS:

Dies, such as those used in drawing out wire, nozzles, such as those on a common garden hose, or jets, such as those used in expelling liquid synthetic fibers into hardening solutions are analogous to the spider's spinnerets.

REFERENCES: 36, p. 6.

Physical Class	Physical Operator	Section 2
Chemistry	Sensors Contact Transformers Information Actuators External	Chemical Production

WHIP SCORPION'S DEFENSE MECHANISM

DESCRIPTION:

The defense mechanism of the whip scorpion (vinegaroon) is a spray-like mechanism that ejects a vinegar-like liquid at antagonists which touch or disturb it.

The liquid is ejected through glands situated laterally to each other in the opisthosoma which is the posterior legless abdominal area. The defensive secretion is stored in the glands, the thin walls of which are composed of the tissues that synthesize the secretion. The ducts of these glands extend posteriorly in a parallel direction and end in a three-sectioned knob just outside of the abdominal wall. It is through these ducts that the stream of repellent is sprayed. A whip or flagellum extends out from the center of this knob-like protrusion. While aiming, the whip accompanies the movements of the knob in such a way that just before discharge it is usually pointed toward, or even brought in contact with whatever has touched the vinegaroon. It would appear that the creature is getting its bearing by using the whip as a feeler, but amputation of the whip does not impair the accuracy with which a discharge through the ducts is aimed.

ILLUSTRATION:

When contact is made with the scorpion's body, the post-abdominal knob and the whip are both turned rapidly and accurately in the direction of the point of contact. During a series of laboratory experiments a vinegaroon was placed in a cage with a small desert mouse. The mouse immediately attacked the whip scorpion. The whip scorpion shot a stream of the irritating secretion at the mouse. The mouse retreated and continued to rub its eyes in an attempt to get rid of the irritating liquid.

MAGNITUDE:

The glands which secrete this irritating liquid have large reservoirs in which the material is stored. As a result, the vinegaroon is able to discharge the fluid many times in succession. The usual number of successive discharges is approximately ten to twelve, although it has been known to discharge as many as nineteen times. The supply of material appears to be almost constant judging from the speed with which the volume of the glandular secretion is restored. The force with which the liquid is expelled allows it to obtain an average distance of over two feet.

WHIP SCORPION'S DEFENSE MECHANISM, Continued:

Chemical analysis of the material shows it to contain 84% acetic acid, 11% water, and 5% caprylic acid. The acetic acid is present in a high enough concentration to be responsible for most of the burning sensation caused by the liquid. However, the presence of the caprylic acid explains the destructive influence of the material, since it is a wax solvent and, when sprayed on insects with a wax coating over their bodies, dissolves the wax and the liquid acts upon the exposed tissues.

SIMILAR EXAMPLES:

The discharge from the poisonous hairs of the nettling insect is similar in immediate action, although the physiological end result is not as severe.

Other repellent-producing creatures include an ant which secretes a mixture rich in citronella, one of the oldest known insect repellents.

Also, there are certain millepedes that secrete hydrogen cyanide (prussic acid).

SAMPLE PHYSICAL ANALOGS:

Tear gas spray guns have been devised for protective purposes. However, these weapons usually employ either plunger or compressed gas to propel the irritant liquid.

REFERENCES: 28, pp. 10-19; 36, p. 57.

SECTION 3:

CHEMICAL SENSITIVITY

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BIOLOGICAL ASPECTS OF CHEMICAL SENSITIVITY

Chemical sensitivity may be defined as the ability of an organism to react to or detect odors and tastes. It is a composite term, which is derived from both the sense of smell and the sense of taste. In the human, the sense of smell is more highly developed and more important than that of the sense of taste, as witnessed by the fact that the receptors of this particular sense are brought into play much more frequently within a man's environment. There is a further distinction on an anatomical and functional level between the receptor organs of the chemical sense. The sense of smell involves primarily a distance chemoreceptor whereas the taste sensation occurs only when there is immediate contact with the stimulus.

A corresponding difference exists on the functional level. Taste only gives information of desirability or undesirability of a particular substance. The sense of smell on the other hand can guide an organism away from danger, towards food, and so on. For this reason, the smell system is connected to an elaborate neural mechanism whereas the taste fibers are in general connected directly with simple motor systems.

It is significant that the lower animals, perhaps because of a lack of the other more highly developed sensory systems, rely heavily on the chemical senses. For some, it is the main means of detecting potential danger and therefore acquires certain survival value. Its superior development plays an active part in the life of the moth, for example. It has been experimentally verified that the male moth can detect the characteristic odor of a chemical given off by the female of his species at distances up to four or five miles.

Chemical cues are nonetheless important to higher animals as well. In these cases, complex systems are involved for computing associations and for making predictions; food, companions, danger and other factors are associated with characteristic chemical conditions.

PHYSICAL ANALOGS IN GENERAL

The complete details of how the taste sensations are produced are unknown, but while a variety of artificial chemical detectors have been constructed, none of the artificial devices are analogs of taste sensors except in a very general way.

The situation with regard to olfactory sensations is slightly better understood in that a scaling of olfactory sensations has been developed. This scaling in many respects

resembles the scaling of color in that a wide variety of olfactory sensations can be produced by mixing four primary odor-producing substances in varying amounts. It has also been suggested that electromagnetic radiation in the long infrared portion of the spectrum is a stimulus for olfactory sensations.

From the standpoint of a chemist who must design chemical detectors, the only difference between taste and smell is the medium in which material is dissolved or suspended, i.e., liquid or gaseous. Since the details of the processes are unknown at this time, it would be purely fortuitous if we could design chemical detectors with sensitivity and range properties resembling those of the human senses. However, we can surmise that the chemical senses might be simulated, as are sight and hearing, by means of a collection of sensors with differing characteristics in combination with suitable parameterization and discrimination equipment.

Physical Class	Physical Operator	Section 3
Chemistry	Sensors Actuators Contact External Distance	Chemical Sensitivity

CHEMOTROPISM

DESCRIPTION:

Chemotropism is the reaction of animals to chemical stimulation of the sense of smell or taste. It may also result in the control of an animal's positioning.

In order for an animal to react to chemical stimulation, the chemical stimuli cannot be at a distance; there must be an actual transfer of material--by diffusion or the like--from the source to the animal.

Animals in general use chemotropism to find food and search for a mate. More rarely is chemotropism involved in escape reactions.

ILLUSTRATION:

Positive chemotropism is demonstrated by the Drosophila (fruit fly) in its attraction to overripe fruit. Yeast cells metabolize the sugar in the fruit which results in the production of certain alcohols and organic acids. This reaction causes the fruit to undergo fermentation. The olfactory organs of the Drosophila are particularly sensitive to these alcohols and organic acids. They attract the fly which then feeds on the yeast cells.

MAGNITUDE:

The degree of chemotropism, either positive or negative, exhibited by any organism depends on the type of compound eliciting this response, and its concentration. Both forms of chemotropism, however, are observed more frequently and more actively in the lower forms of animal life.

SIMILAR EXAMPLES:

Other examples of positive chemotropism are:

The attraction of male moths to the scent emitted by female moths even at a great distance.

The grasshopper's method of finding food, mates and shelter.

SAMPLE PHYSICAL ANALOGS:

The existence of a tropism usually depends on the existence of a suitable detector and on a means for detecting the direction of the maximum gradient of the signals or stimuli. Methods of detecting the direction of maximum signal strength (direction finding methods) are commonly employed in radio and radar work, especially in military countermeasures activities. In computer programming, techniques for searching function

CHEMOTROPISM, Continued:

spaces and following that direction (or its opposite) to locate maxima (or minima) in the space are often called "hill-climbing" methods.

REFERENCES: 36, p. 212; 102, p. 504; 140.

Physical Class	Physical Operator	Section 3
Chemistry Fluid Mechanics Materials Properties	Sensors Internal Transformers Energy Matter Actuators Internal	Chemical Sensitivity

EFFECT OF NICOTINE ON THE INSECT'S HEART

DESCRIPTION:

Nicotine acts variously in different insects. In Periplaneta americana it accelerates the rate of heart beat in low concentrations. With intermediate concentrations initial stimulation is followed by partial depression, and with high concentrations the initial stimulation is followed by systolic standstill. Although the heart of Prodenia eridania is less sensitive to nicotine than that of the cockroach, it is similarly stimulated and depressed, although final standstill occurs in diastole rather than in systole.

ILLUSTRATION:

The combination of all the cardiovascular effects of nicotine results in a sustained decrease of the systolic and pulmonary arterial pressures. This effect is more accentuated in the adult insect than in the young.

Nicotine abolishes all the ganglionic and preganglionic reflexes that maintain circulatory homeostasis. The vascular system becomes so passive that it cannot redistribute the large volume of blood that accumulates by gravity in the capillary system.

MAGNITUDE:

The nicotine present in the fumes of burning tobacco will stop the heart action of Macrosiphum tulipal in two to three minutes.

SIMILAR EXAMPLES:

DDT produces similar results on the action of many insects especially of the insect Periplaneta.

SAMPLE PHYSICAL ANALOGS:

In most other entries in this section, specialized cells provide a detection capability, giving an informational coupling between organism and environment. The effect of nicotine on the insect's heart is a true sensitivity, rather than a detection.

If an elementary information or signal processor is taken as a model of a living organism, the specialized cells that provide a detection of chemicals can be equated to a transducer that provides inputs to the information processor. The sensitivity of tissues to chemicals has as its counterpart a mechanism for modifying the signal processing of the processor. In more concrete terms, the potentiometers in analog computers provide a direct means for modifying the transfer function of the computer. These potentiometers thus constitute a mechanism for producing

EFFECT OF NICOTINE ON THE INSECT'S HEART, Continued:

an effect analogous to that of nicotine on the insect's heart.

REFERENCES: 6, pp. 263-264.

Physical Class	Physical Operator	Section 3
Chemistry Fluid Mechanics	Transformers Matter	Chemical Sensitivity

GILL SLIT

DESCRIPTION:

The gill slit is an opening from the side of the pharynx to the exterior of the body in aquatic chordates. These openings are usually vertically elongated, with several lying in a series, one behind the other, on each side, and separated by cartilaginous bars which support the pharyngeal arch. Traces of these can be found in mammals. The first slit is joined at the mouth, the second forms the hyoid gill cleft and the rest, the bronchial clefts. Primitively, they were probably concerned with filtering food particles from water pumped through them by action of cilia, as in tunicates and amphioxus.

ILLUSTRATION:

In fish and some Amphibia, the gill slits serve as organs of respiration in which the water pumped through by muscular action oxygenates the blood in the gills. The blood flows in opposite direction to the water outside the surface providing a rapid process and almost complete saturation as the blood leaves the gill filaments.

Aquatic Crustacea have gills which are usually ventilated by the paddle-like motion of special appendages such as the scaphognathites.

Many aquatic insects have gills through which oxygen passes directly to the branched tracheae. These are found in nymphs of Odonata, Plecoptera and Ephemeroptera.

MAGNITUDE:

With some Crustacea, having an increased ability to remain on land results in a corresponding reduction of gills. For instance, the number of gills in low-tide crabs is approximately 26, in high-intertidal species it is 18, and in a beach crab, 12. Similarly, intertidal crabs have a gill area of 624 mm^2/g, while land crabs have an area of 325 mm^2/g.

The amount of saturation may vary with the amount of movement. Fish which were swimming had blood 85% saturated with oxygen whereas the blood of stationary fish was only 11% saturated.

SIMILAR EXAMPLES:

Although the gill slits are absent from most adult tetrapods, the presence of gill slits, or at least of gill pouches and corresponding epidermal grooves at some stage of development, is characteristic of the whole Phylum Chordata. Gills perform a function similar to that of lungs.

GILL SLIT, Continued:

SAMPLE PHYSICAL ANALOGS:

Underwater breathing apparatus normally makes use of stored oxygen or air pumped from the surface. No practical use has ever been made of equipment to liberate and utilize the oxygen dissolved in water, although experimental equipment has been constructed for this purpose.

REFERENCES: 58, pp. 362-380; 116, pp. 155-156; 150, p. 57; 152, p. 727.

Physical Class	Physical Operator	Section 3
Chemistry	Sensors Distance	Chemical Sensitivity

HOMING MIGRATION OF SALMON

DESCRIPTION:

The homing of salmon is accomplished as a result of the fish's sense of smell. After a young salmon has lived for some time in a fresh-water stream where it was hatched, it follows the stream to the ocean. It may stay in the ocean from one to several years, but when it is ready to spawn it returns to the stream in which it was born.

ILLUSTRATION:

After experiments in special aquaria, Wisconsin zoologists proved that fish were able to distinguish such "odors" as those of various plant solutions and also waters from different rivers and streams. This led to an extensive field experiment in the state of Washington. During a spawning season, mature salmon that had returned to spawn were taken out of two different branches of the Issaquah river. Half the fish had their noses plugged with cotton and then all the fish were taken downstream and released.

Those salmon with plugged noses migrated back upstream, but picked the wrong stream as frequently as the right one. Those with unplugged noses always returned to the stream where they were hatched. Many subsequent experiments have confirmed that young salmon are "imprinted" with whatever odor (or taste) they experience at the time of hatching, and then have a tendency to seek this out again on maturation.

MAGNITUDE:

The extent of this chemical sensitivity was shown when investigators discovered that fish were able to distinguish the odors of very dilute rinses of many water plants in laboratory experiments. In one study, Canadian investigators marked approximately 470,000 sockeye salmon in the Fraser river. During the following few years, nearly 11,000 of these were recovered in that river as they returned from the ocean. None of them was found to have strayed into another stream.

SIMILAR EXAMPLES:

Pigeons, ducks, chickens, and other birds also exhibit the phenomenon of homing.

The small hole covered by a transparent tissue in the top of the tuna's head may, according to the Nova Scotia Fisheries Department, explain the fish's migrations as the result of seasonal sunlight changes. The hole is connected to a tube leading to the tuna's brain. Also, see entry on "Chemotropism".

HOMING MIGRATION OF SALMON, Continued:

SAMPLE PHYSICAL ANALOGS:

Odor detection devices, gas detectors, and chemical sensing instruments perform functions similar to the fish's sense organs.

See comments on Physical Analogs in General at the beginning of this section.

REFERENCES: 129, pp. 89-90.

Physical Class	Physical Operator	Section 3
Chemistry	Sensors Transformers Distance Information	Chemical Sensitivity

OLFACTORY SACS IN SHARKS

DESCRIPTION:

Sharks can detect odors faster in water than many land animals can in their natural habitat although the diffusion of odorous substances through water is much slower than through air. This is accomplished by the passage of the water through the olfactory sacs, two invaginated shallow pockets located on the ventral surface of the snout.

ILLUSTRATION:

Sharks are known to be able to discover a dead body at considerable distance in a very short time. However, when the nasal pits are plugged, the shark is unable to locate odorous food readily, even in the immediate vicinity.

MAGNITUDE:

Compared to other fish, the shark is known to have one of the most highly developed and most sensitive olfactory systems.

SIMILAR EXAMPLES:

The sea lamprey has one nasal aperture which leads into the olfactory sac. This sac receives nerve endings from both olfactory lobes of the brain.

The planaria, a flatworm, has ciliated pits, located on both sides of its head, which contain special sensory cells with long cilia. These are probably organs of a chemical sense that aid in finding food.

The reactions of the crayfish to food are partly due to the chemical or olfactory sense organs located in its smooth hairs. Each of these hairs has a nerve bundle in it which reacts to chemical stimulation. Although these smooth hairs are found on almost all of the crayfish's appendages, they are much more numerous on the anterior ones, with the exception of the "first" legs or chelipeds. Positive reaction results from the application of food substances; acids, salts, sugars, and other chemicals produce a negative reaction indicated by scratching or pulling at the part stimulated.

SAMPLE PHYSICAL ANALOGS:

Odors can be measured by an electronic "nose" and the differences between them plotted by an electronic sorting apparatus which uses common substances, such as salt or egg albumen, to absorb odor particles in a gold lined chamber, creating an electrical impulse that can be read on an oscilloscope. Dr. Andrew Dravneiks, consultant to Armour Research Foundation, has constructed a device of this type. He utilized the absorbers, such

OLFACTORY SACS IN SHARKS, Continued:

as the salt, which simulates the way the moist membrane in the human nose picks up odors and creates electrical impulses which are interpreted by the brain.

REFERENCES: 25; 58, p. 396; 140, p. 390; 144, p. 771.

Physical Class	Physical Operator	Section 2
Chemistry	Sensors Transformers Distance Information	Chemical Sensitivity

OLFACTORY SENSITIVITY IN CRAYFISH

DESCRIPTION:

The reactions of the crayfish to food are due partly to the chemical or olfactory sense organs located in its smooth hairs. Each of these hairs contains a nerve bundle which reacts to chemical stimulation. Although these smooth hairs are found on almost all of the crayfish's appendages, they are much more numerous on the anterior ones, with the exception of the "first" legs or chelipeds. These chelipeds are larger and longer than the other legs, and have at their ends the pinchers or grasping organs.

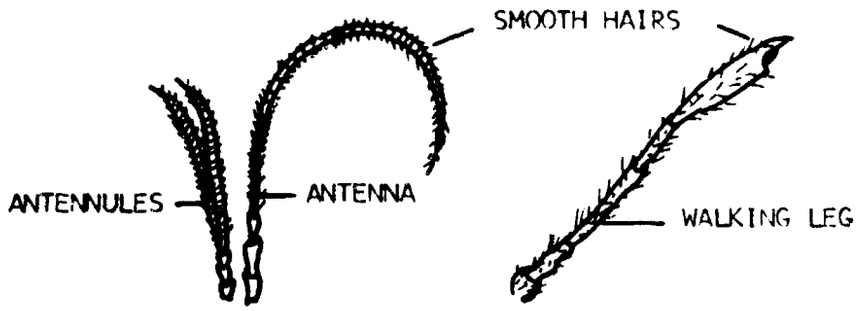

FIG. 2 SMOOTH HAIRS ON CRAYFISH APPENDAGES

ILLUSTRATION:

Since crayfish react to olfactory stimulation on any part of the body, it can be assumed that there are olfactory organs on the entire body. The anterior appendages, however, are the most sensitive, especially the outer ramus of the antennules. Positive reactions result from the application of food substances. For example, if meat juice is placed in the water near the animal, the antennae move slightly and the mouth parts perform vigorous chewing movements. The meat causes "general restlessness" and vague movements toward the source of the stimulation, but the animals seem to depend chiefly on touch for the accurate localization of food. Acids, salts, sugars and other chemicals produce a negative reaction indicated by scratching the carapace, rubbing the chelae or pulling at the part stimulated.

MAGNITUDE:

The extent of the reaction has been shown to depend directly on the concentration (or dilution) of the chemical

OLFACTORY SENSITIVITY IN CRAYFISH, Continued:

stimuli in the area of the crayfish.

SIMILAR EXAMPLES:

In some respects these smooth hairs could be compared with the sensitive olfactory hairs of insects.

SAMPLE PHYSICAL ANALOGS:

See Sample Physical Analogs in the entries "Olfactory Sacs in Sharks" and "Taste Buds" in this section.

REFERENCES: 58, p. 396.

Physical Class	Physical Operator	Section 3
Chemistry Mechanics	Sensors Transformers Distance Information	Chemical Sensitivity

OLFACTORY SENSITIVITY IN INSECTS

DESCRIPTION:

Insects have attained a high degree of specialization in olfaction. Some of their receptors are particularly sensitive to volatile materials, hence are called distance olfactory organs; these are often on antennae, sometimes on labial palps; and they may be pore plates (sensilla placodea), thin cones and pegs (sensilla basiconica), or pegs or cones in pits (sensilla coelaconica).

ILLUSTRATION:

The olfactory sensitivity of an insect to a chemical depends both on stimulation of the sense organ and on central nervous responses.

Some of the male night-flying moths are able to fly for miles through darkness, following scent trails of female moths through the air.

MAGNITUDE:

Through two inches of solid wood the ichneumon fly can smell the grub on which it lays its eggs.

A monarch butterfly's olfactory sensitivity is 1,200 times as sensitive as that of man in detecting certain substances.

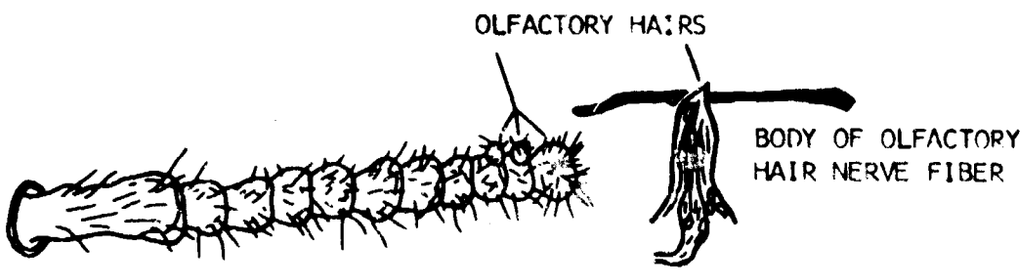

FIG. 3 INSECT ANTENNA WITH OLFACTORY HAIRS

SIMILAR EXAMPLES:

The olfactory sensitivity of the honey bee is very similar to that of man. The following compounds are each distinguishable by bees and man alike: amyl acetate, methyl heptenone, bromstyrol, isobutyl benzoate and salicylic acid.

OLFACTORY SENSITIVITY IN INSECTS, Continued:

SAMPLE PHYSICAL ANALOGS:

See Sample Physical Analogs in the entries "Olfactory Sacs in Sharks" and "Taste Buds" in this section.

REFERENCES: 119, pp. 544-556.

Physical Class	Physical Operator	Sensing
Chemistry	Sensors	Chemical
	Contact	Sensitive

TASTE BUDS

DESCRIPTION:

The taste buds or gustoreceptors are composed of taste sensory cells grouped in clusters. Although they are generally similar among vertebrate animals, their principal difference is in their arrangement and distribution.

A taste bud consists of two types of cells:

a. Sensory receptor cells which are slender and elongated with enlarged basal ends. Their peripheral terminations are in spaces formed by the converging tips of the sustentacular cells.

b. Sustentacular cells - These surround the sensory cells and are of two types.

1. Basal cells - considered by Rauber to be reserve cells for renewal of the cells in the cluster.

2. Elongated supporting cells - both peripheral and interstitial, which give the taste bud its oval shape.

There are four generally accepted taste sensations which can be demonstrated in man by the location of their receptors on the tongue. These are: sweet, sour (or acid), salt, bitter.

Sensation	Location of Lowest Taste Threshold in Man
Sweet	at the front of the tongue
Sour (acid)	at the sides in areas of the tongue overlapping with salt taste buds
Salt	at the sides in areas of the tongue overlapping with sour
Bitter	at the back of the tongue

In reptiles, such as crocodiles and snakes, the taste buds are in the posterior part of the mouth cavity.

Although taste buds are scarce in birds' mouths, a few are found in the posterior part of the tongue, embedded in the lingual papillae.

In many mammals there are only two areas of the tongue that are free of taste buds, i. e., the central oval area on the upper surface and the area under the tongue.

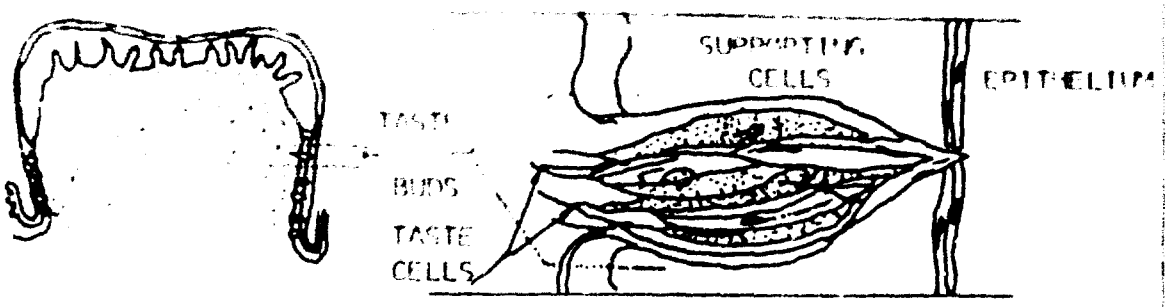

FIG. 4 TASTE BUDS

ILLUSTRATION:

In fish, such as carp, suckers, and catfish, the taste sensitivity extends over the entire ectodermal covering of the body. However, chemical sensors exhibit their greatest elaboration among mammals.

MAGNITUDE:

Man can detect the presence of quinine in as low a concentration as one part in 1,000,000 parts of water.

Some taste bud fibers respond to acids, at or below a specified pH, such as 2.5. Others respond to sodium chloride, NaCl, in solutions more dilute than 0.03 molar concentration. Related to these fibers are the salt taste endings which require a higher NaCl concentration than 0.05 molar.

Some fibers of the chorda tympani nerve in various animals respond when the tongue is bathed in distilled water, indicating that some receptors will respond to an increase in ions and others to a decrease.

SIMILAR EXAMPLES:

There are many other examples of unusual taste responses which illustrate the action of individual taste bud specificity. For example, a cat usually does not exhibit a taste response to the presence of sugar in solution, whereas a rabbit will. A taste reaction observed in many dogs is their ability to differentiate between sugar, which they appear to like, and saccharine, which they appear to dislike.

SAMPLE PHYSICAL ANALOGS:

Devices for the detection or identification of chemicals in aqueous or gaseous solution and pH meters provide functions analogous to those of taste buds. Various physical and chemical principles have been employed in the detection or identification of chemicals. For example, spectroscopic analysis of compounds is commonly employed. Spectrometers are also used to identify an element or compound, but depend on the mass of the material rather than upon chemical reaction for identification.

TASTE BUDS, Continued:

Gas detectors and leak detectors are usually designed to respond to a group or family of materials having some common property and normally are not designed to identify individual elements or compounds. For example, electrical properties of materials, such as conductance or permeability, are sometimes used to determine the concentrations of liquids.

REFERENCES: 7, pp. 1458-1459; 44, p. 1094.

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BIOLOGICAL ASPECTS OF ELECTRICAL ENERGY

Numerous types of animal tissues such as the nervous and muscular tissues generate small electric currents. Bacteria likewise produce electrical energy. Useful power has been developed in "biological fuel cells" employing bacteria. Electrical energy is produced in two general ways by animals. The first and more common one is the generation of electricity by the various tissues; the second is the production of a far stronger current by fish having specific electric organs.

Two examples of the production of electric currents by human tissue are: (1) the heart, which produces a measurable current at the surface of the body, and (2) the brain, which produces a small amount of electricity which can be detected by the electroencephalograph.

Among the current-producing animals, there seem to be two general groups of electric organs with respect to their intensity of production. One group produces the current used mostly for offense and defense. The other group produces a weak current used mostly as an echo-location mechanism.

In the following section, we describe the principles involved in the production of electric current by fish, and also by the human organs mentioned.

PHYSICAL ANALOGS IN GENERAL

In terms of total quantity of energy produced, the induction of currents in a conductor moving through a magnetic field is the most common method of generating electrical energy. This type of electrical production does not appear in nature probably because strong natural magnetic fields do not appear often on earth.

Since the chemistry of redox reactions has been studied fairly extensively, we are not likely to learn many new chemical facts from studies of electricity production in living cells. The existence of the bacteriological fuel cell, although still in the research phase, is an indication of the type of application which may arise.

Physical Class	Physical Operators		Section 4
Electricity and Magnetism Mechanics	Transformers Energy Information	Actuators External Internal	Electrical Energy

ELECTRICAL RESPONSE IN NERVE AND MUSCLE CELLS

DESCRIPTION:

Nerve cells and muscle cells will respond to electrical stimulation. If a sufficiently strong current, i.e., one exceeding the threshold or rheobase, is applied, the nerve responds by starting a normal impulse and the muscle responds by contracting. The first response follows immediately after the current begins to flow. Thereafter it is a change in the current, rather than its mere presence, which evokes further response.

If the stimulation consists of a single, short electric pulse applied to the muscle, a brief latent period passes before the contraction occurs. Additional delay occurs if stimulation is applied to the nerve rather than to the muscle itself, the impulse then having to traverse the nerve first.

When a second stimulus is applied before the first contraction ends, a new contraction is superimposed on the first. If closely spaced stimuli are applied continuously, the result is a smooth, sustained contraction called tetanus. This type of activity is normally found in the skeletal muscles of vertebrates.

ILLUSTRATION:

A specific characteristic of vertebrate muscle contraction is the all-or-none phenomenon. In this case the contraction is complete as long as the stimulus exceeds the threshold. Increasing the strength of the stimulus does not affect the magnitude of the response. The heart, contracting as a single unit, typifies this type of activity. The variance in degree of contraction is due to the activity of the fibers themselves rather than changes in stimulation. Similarly, the changes in the response of the striated muscle when subjected to stimuli of varying strength, are due to the activation of a variable number of contractile units, each of which, however, is responding maximally.

MAGNITUDE:

Tissues that respond slowly have a higher rheobase and a longer chronaxie than those which respond rapidly. The frog gastrocnemius muscle has a chronaxie of 0.3 ms and a contraction time of 0.15 sec; gastric muscle in the same species has a chronaxie that varies from 30 to 100 ms and a contraction time between 15 and 20 sec; the pigment cells in the frog's skin also react slowly, their chronaxie being from 11 to 15 sec.

SIMILAR EXAMPLES:

Hiccoughs (or singultus) are similar in that stimulation of the afferent nerve terminals will result in a spasmodic contraction of the diaphragam. Other types of muscular spasms are also

ELECTRICAL RESPONSE IN NERVE AND MUSCLE CELLS, Continued:

activated in a similar manner.
See also "Babinski Reflex Effect".

SAMPLE PHYSICAL ANALOGS:

Any device with a threshold and which saturates with no stable states between saturation points is analogous. A bi-stable multivibrator is one such device although a single pulse (stimulus) switches it from one stable state to another. An additional pulse is required to reverse the action. A mono-stable multivibrator responds to a pulse input by switching from one stable state to another but returns to the original state after a time lapse. Latching and time-delay relays are similar in action.

Gas tubes have a characteristic of complete conduction as long as the input signal exceeds the threshold required to start ionization of the gas. Some solid state devices as well as circuits exhibit this characteristic.

REFERENCES: 7, p. 477; 68, pp. 776-778, 794, 816.

Physical Class	Physical Operator	Section 4
Electricity and Magnetism	Sensors: Distance; Actuators: External; Transformers; Energy	Electrical Energy

ELECTRIC CURRENT PRODUCTION IN FISH

DESCRIPTION:

Both fresh and salt water electric fish are able to generate heavy electric discharges. The electric organs involved in this process are derived from the muscular tissue. They are composed of a large number of disc-like coils called electroplates, or electroplaques, which are arranged in a series and/or parallel grouping. The two sides of the electroplates are different, only one side being supplied by a cranial or spinal motor nerve. All the electroplates face in the same direction, thereby producing an additive effect which is capable of building up high voltages.

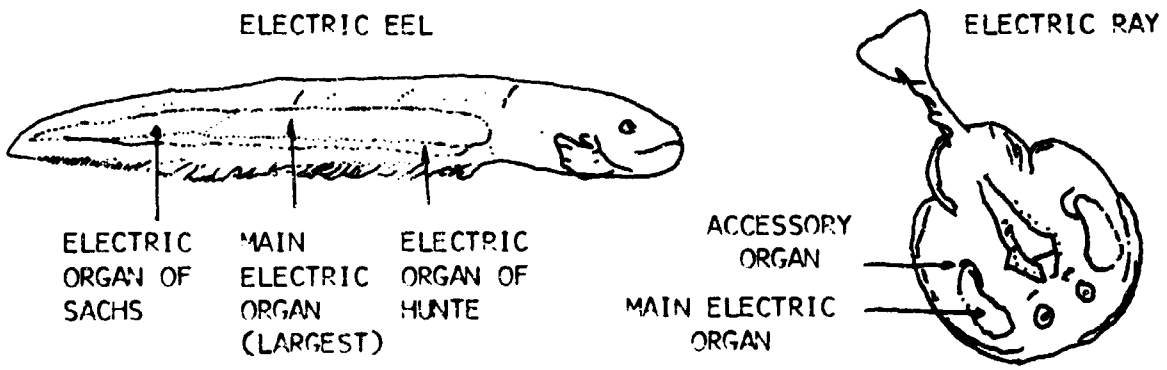

FIG. 5 ELECTRIC ORGANS IN THE EEL AND RAY

ILLUSTRATION:

Fish producing a strong electric current use this mechanism for both offense and defense. Those fish which produce weak electric currents use these organs as part of a locating mechanism. Both groups are extremely sensitive to the influences that affect or interrupt their electric fields in the water.

With each discharge, the fish sets up an electric field resembling an electric dipole. Those objects with an electrical conductivity differing from that of the water will change the normal pattern of this field around the fish. Investigators believe the fish can detect these changes in their electric fields by special receptors. These receptors serve to distinguish between conductors and nonconductors in the water and also to determine the presence and location of other fish.

MAGNITUDE:

The strong electric fish, such as the Electrophorus, the Malapterurus, and Torpedo, produce discharges in short trains between 5 and 20 pulses, each one being about 1 ms in duration.

ELECTRIC CURRENT PRODUCTION IN FISH, Continued:

The recorded voltage of the discharge from the whole organ is determined by the activity of the total number of electroplates. The total number of these plates in the electric eel, for example, has been determined by Keys to be in the vicinity of 6 to 7 thousand plates.

Grundfest, in his article on electric fish, listed the voltage output of a number of them as follows:

a. The Electrophorus (electric eel) of South American rivers can produce a potential of more than 500 v.

b. The Malapterurus (African catfish) can produce a potential up to 350 v.

c. The Torpedo nobiliana (giant electric ray) which inhabits the North Atlantic Ocean can produce potentials of 50 to 60 v, the latter being at 50 amp.

The weak electric fish may produce discharges as low as a fraction of a volt, and in many cases these discharges are maintained continuously and with regular frequency throughout their life span. This type of fish is not affected by the fish's state of excitation. Other types of weak electric fish, such as the Momicidae and Gymnotidae produce a slow and irregular discharge at an approximate rate of 1 to 6 each second, increasing when the fish is excited. In this case, the discharge duration from the whole organ can be as short as 2/10 ms.

In one species of fish studied by Professor Lissman of Cambridge University, it was found that the fish, Gymnotidae, were sensitive to a change in the field in the water of 3×10^{-9} and could discriminate between different-size glass rods in the tank by this mechanism.

SIMILAR EXAMPLES:

The physiology of the electric organ in fish is similar to that of a muscle, although different in effect. The electric charge in the electroplate and the surface potential in a muscle fiber both are positive on the outside in relation to the inside. During the discharge, the charge is reversed on the face receiving the nerve. The entire electric organ consists of a large number of electric cells arranged in series.

SAMPLE PHYSICAL ANALOGS:

Chemical fuel cells, biochemical fuel cells and the electrolytic wet-cell batteries are analogous in that the electric energy produced depends on chemical reactions.

A device used to produce a current for spot welding is analogous in operation but not in means of energy production. This machine is arranged so that a large number of capacitors are charged over a relatively long time in parallel and, after being fully charged, they are switched to a series configuration and allowed to discharge through the metal to be welded. In this manner a high voltage, high current is produced for a very short discharge period.

ELECTRIC CURRENT PRODUCTION IN FISH, Continued:

REFERENCES: 47, p. 115; 77; 90, p. 156.

Physical Class	Physical Operator	Section 4
Chemistry Electricity and Magnetism	Transformers Energy Information	Electrical Energy

PSYCHOGALVANIC RESPONSE

DESCRIPTION:

The psychogalvanic response (PGR) is a widely used index of the level of activation. It involves a measure of the electrical resistance of the skin, usually of the palms of the hands. A change in the response level is caused by the production of an electromotive force in the skin immediately following the application of a stimulus. The response is an especially valuable measure due to the speed and sensitivity with which it follows stimulation.

ILLUSTRATION:

The more generally favored view today is that the response of sweating is the crucial variable in the measurement of the psychogalvanic response. The extent of change in electrical conductance is directly correlated with the actual amount of sweat secreted. Sweating itself is not the cause of the response, but some neural or chemical activity in the skin that precedes sweating probably is.

These sweat glands seem to be innervated by postganglionic fibers of the sympathetic nervous system. Since this system is basic to emotion and, more specifically, to a general activation level, the response gives us excellent measures of these phenomena.

MAGNITUDE:

A correlation between the PGR and words rated on a scale from very pleasant to very unpleasant is quite positive. The response is smallest for stimuli considered "indifferent" with the greatest response occurring to "very unpleasant" stimulus words.

Similarly, when words of ambiguous or conflicting qualities are introduced, the response increases such that the median response to a mixed stimulus was 263 ohms as against 177 ohms for unpleasant stimulus words.

SIMILAR EXAMPLES:

Other electrical activity in the body is found in brain waves as well as in the action potential of muscles.

Similar measuring devices are likewise used to measure uncontrolled or semicontrolled actions such as heart beat, blood pressure, and respiration.

SAMPLE PHYSICAL ANALOGS:

The complete PGR involves many processes and mechanisms. Of these, only the simpler aspects have analogs. For example,

PSYCHOGALVANIC RESPONSE, Continued:

varying the salinity of water changes its conductivity. However, the PGR has, itself, been incorporated into the polygraph (lie detector) since it provides some indication of emotional activity.

REFERENCES: 108, p. 556-557; 145, pp. 137, 154-155.

Physical Class	Physical Operator	Section 4
Chemistry Electricity and Magnetism	Transformers Energy Actuators Internal	Electrical Energy

THE SODIUM PUMP AND ELECTRICAL POTENTIAL

DESCRIPTION:

When a single fiber in a muscle is at rest, a difference in potential exists between the inner and outer surfaces of the fiber, the latter being positive with respect to the former. This potential difference is due to the excess of positive ions on the surface, resulting from an active transport of sodium from the inside to the outside. This transport mechanism is commonly referred to as the "sodium pump".

ILLUSTRATION:

It has been claimed that only the membrane ionic hypothesis can adequately explain this phenomenon. According to this view the resting potential of the muscle fiber is due to the relatively free diffusion of the small potassium and chloride ions across the membrane and the rather limited diffussion of the sodium ions. As a result, an electrical potential difference is set up across the membrane so that there is little or no electrochemical potential gradient of the freely moving potassium and chloride ions across the membrane despite the large differences in concentration.

The pump mechanism allows for the maintenance of these differences in concentration along with the very low internal concentration of sodium.

MAGNITUDE:

The potential difference between the inner and outer surfaces of the muscle fiber is about 90 to 100 mv.

In the giant axons of squid, the resting potassium and sodium conductances are about 0.5 and 0.01 mmho per cm^2 respectively.

SIMILAR EXAMPLES:

The muscle fibers can be depolarized in several ways: by mechanical stimulation, by a change in pH, or by the application of chemicals. The usual manner, however, is the arrival of a nerve impulse.

See also "Membrane Permeability".

SAMPLE PHYSICAL ANALOGS:

A physical analog to the sodium pump phenomenon is an ultrafiltration membrane, the thickness of which is related to the Fick diffusion coefficient. The driving force for the ultrafiltration is the chemical potential according to the Fick coefficient. If interference between the components is

negligible, the flow rate of each component is dependent upon the change in its own chemical potential as it passes from the solution on one side of the membrane to that on the other side. This chemical potential is directly proportional to the degree of change.

REFERENCES: 30, p. 62; 68, p. 784; 129, p. 70.

SECTION 5:

EQUILIBRIUM SENSING AND CONTROL

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BIOLOGICAL ASPECTS OF EQUILIBRIUM SENSING AND CONTROL

The ability of an organism to maintain its equilibrium and to stay oriented with respect to the local vertical depends upon the existence of specialized sensing organs and upon specialized reactions or responses to forces or to changes in orientation. Not all organisms maintain a preferred orientation with respect to gravity, however. The Volvox, for example, has no preferred orientation and maintains an indifferent equilibrium.

In the lower forms of animal life, equilibrium sensing is accomplished by statocysts, which are hollow, cell-like structures containing a small granular formation like a piece of sand. Changes in an animal body position cause the granule to roll or fall against small, hair-like projections on the inner surface of the statocyst. In the crayfish, nerves from the statocysts connect to the ganglionic nerve center.

The most highly developed organs of equilibrium are the semicircular canals found in the higher animals, such as man. Studies have shown, however, that man does not rely completely on signals from the semicircular canals to maintain equilibrium. Sight, touch, and proprioception play significant roles in equilibrium maintenance.

Responses or reactions of animals to changes in position or to bodily contact (or lack thereof) take many forms. Some of the types of contact orientation taxes and reactions are described below.

1. Thigmotaxis is a form of response exhibited in many crawling animals. It involves a search for shelter and protection. (See "Thigmotaxis" on page 277.)

2. Rheotaxis is the orienting response of an animal with respect to a current of water. It is exhibited by such microscopic water organisms as euglena, hydra, and paramecium. (See "Rheotaxis" on page 273.)

3. Anemotaxis is the orienting response of an animal to air currents. This response is characteristic of many flying insects. (See "Air Current Sensors" on page 264.)

4. A righting reaction is exhibited by the starfish, crayfish, snail, and some insects, such as the click beetle. This reaction is considered to be a form of position-orienting

response since the animal makes an attempt to regain the contact of its appendages and ventral surface to the ground.

PHYSICAL ANALOGS IN GENERAL

Biology is rich with examples of the use of feedback mechanisms to stabilize, regulate, and control. Of particular importance to the preservation and propagation of life is the maintenance of suitable equilibrium of biological systems with respect to their environment. One of the more obvious examples of the maintenance of equilibrium is the ability of the healthy members of warm-blooded species to regulate body temperature within narrow limits.

Both complex and simple mechanisms are used to maintain equilibrium of biological systems. Nevertheless, these mechanisms always involve, as a minimum, some means for (1) sensing system deviations from desired equilibrium conditions, and (2) taking action to reduce these deviations. In the language of servomechanism engineering, the equilibrium is maintained via a feedback loop, which, in addition to the process being controlled, contains elements for

- sensing
- computing
- actuating

A system block diagram is often drawn to show the relationships between these elements:

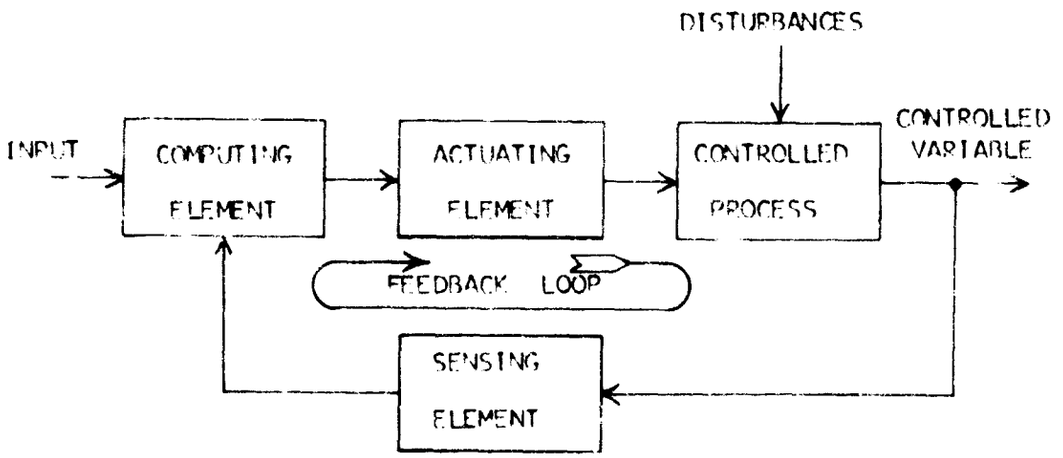

FIG 6. TYPICAL FEEDBACK CONTROL SYSTEM

The input consists of information concerning desired values of the controlled variable, which may be affected in an unpredictable manner by various environmental disturbances.

The input in a biological system is frequently of an implicit or hereditary nature, that is, the sensing element is structured to produce an error signal expressing system deviations from equilibrium conditions. Under these circumstances, the block diagram reduces to

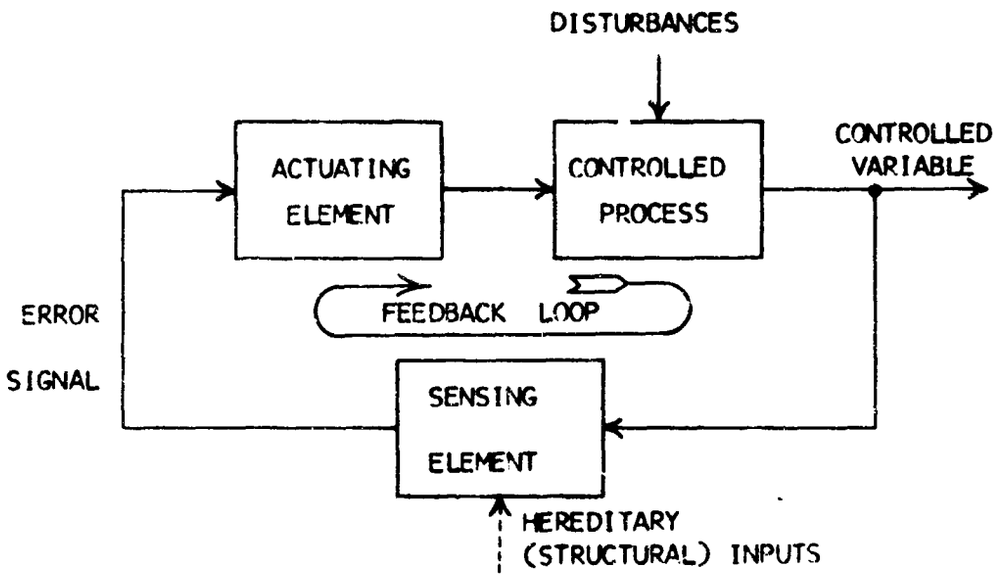

FIG. 7 MODIFIED CONTROL SYSTEM TYPICAL OF INSTINCTIVE BEHAVIOR

Biological application of basic control and regulating principles are so profuse that this section can only begin to present the subject, although an effort has been made to include several of the more subtle phenomena. Furthermore, the study of biology is rarely approached from the standpoint of identifying feedback paths and key elements within these paths, with the result that the literature is confined largely to phenomenological descriptions of the maintenance of equilibrium, existence of certain tropisms, etc. For instance, geotropism exhibited by plants would suggest that they possess a highly sensitive means for detection of the gravitational gradient. Knowledge concerning the sensing technique(s) that plants use for the purpose, however, is very sketchy.

In summary, the mechanisms of biological equilibrium obey the physical principles common to engineering control and regulating systems. But, before thoroughgoing analysis of biological techniques and devices becomes possible, a slightly different set of questions will have to be asked, and biological investigators must set out to answer these questions. In particular, we anticipate that the study of biological transducers (sensors) will pay rich dividends in the advancement of the science of bionics.

Physical Class	Physical Operator	Section 5
Aerodynamics Mechanics	Sensors Contact Internal Actuators External	Equilibrium Sensing and Control

BALANCE AND FLIGHT OF INSECTS

DESCRIPTION:

The occurrence of any imbalance of an insect during flight results in (a) pitching or rotation antero-posteriorly about the transverse axis, (b) rolling about the longitudinal axis, and/or (c) yawing about the dorsal-ventral axis. The sensory input for insects is partly visual, partly by wing sense organs (especially in insects with two pairs of wings), partly by sensory organs (hairs) at the region of the head attachments in Odonata, and partly by halteres or modified hindwings in Diptera. The halter is a dumbbell-shaped organ resembling one arm of a tuning fork in action. It has one or two muscles and an abundance of campaniform sensilla, or sensory hairs, at its base. These halteres, of which there are two on an insect, form an integral part of the wing sense organ system of numerous insects. Removal of the halteres seriously interferes with the ability of an insect to fly, and particularly affects its ability to maintain orientation in the horizontal plane.

ILLUSTRATION:

In the balance and flight of insects a gyroscopic torque is produced which fluctuates at twice the frequency of halter oscillation, and sensory nerve impulses from the halteres show a burst for each half-cycle of oscillation.

During yawing, the nerve discharge is augmented much more than during rolling, although each halter can indicate rotations about both yawing and rolling axes, and the central nervous system can resolve pitch. The halter muscle contractions are more frequent than the impulses of the activating nerves, and the frequency depends on the mechanical properties. The vibration is in synchronization with the wing motions.

Removal of one halter and blinding the insect results in very erratic flight. Removal of both halteres results in uneven flight and inability to maintain normal attitude in flight.

MAGNITUDE:

The halter nerve of insects contains several hundred incoming fibers; the principal nerve to the flight musculature contains about six motor axons. Although it is probable that the complete innervation of the flight muscles is appreciably more complex than these figures indicate, the disproportion between sensory and motor elements justifies the inference that spatial and temporal summation at the central synapses is of great importance to maintain a level of central tone, without which motor activity would be depressed or improperly coordinated.

BALANCE AND FLIGHT OF INSECTS, Continued:

SIMILAR EXAMPLES:

The semicircular canals in vertebrates are important equilibrium devices, as is the statocyst of the crayfish discussed elsewhere in this section. The ability to sense pitching, rolling, and yawing motions is necessary for birds to maintain balance during flight, and is derived from numerous senses such as vision and proprioception. Birds may utilize the sensing of polarization of light from the sky. See, also, "Air Current Sensors", in this section.

SAMPLE PHYSICAL ANALOGS:

The halteres in Diptera do not achieve continuous rotation of the sensory mass, but are constrained to oscillate in harmonic motion. The angular momentum of the halteres is, therefore, relatively small. Nature appears to have compensated for the lack of large angular momentum by use of an extremely sensitive torque-measuring apparatus, presumably the campaniform sensilla at the base of the halteres.

The function of the halteres is analogous to gyroscopic instruments used to sense angular rates of flight vehicles; however, a gyroscope employs continuous rotation of the sensory mass.

REFERENCES: 19, p. 577; 116, pp. 302-304.

Physical Class	Physical Operator	Section 5
Fluid Mechanics Mechanics	Sensors Actuators Internal External	Equilibrium Sensing and Control

GEOTROPISM

DESCRIPTION:

Geotropism is the process of orientation with respect to gravity. Positive geotropism refers to orientation or turning toward the gravitational source, whereas negative geotropism is orientation away from the source. These two manifestations may possibly reverse themselves with subsequent stages in a life cycle, or with competing stimuli.

ILLUSTRATION:

Geotropism is brought about by the arrangement of the component parts within the responsive cells, which in animals may be statocysts, proprioceptors, and possibly cutaneous sense organs. These may cause a series of postural reflexes resulting in geotropism. Positive geotropism is exhibited by turbellarians, holothurians, brachiopods, some larvae and certain snails when burrowing into the mud or sand. In polychaetes for example, the direction of burrowing is sensed by statocysts.

MAGNITUDE:

There appears to be little information available concerning the ability of animals and plants to sense the magnitude of apparent gravity, although an abundance of data substantiates the ability of many species to sense the direction of the gradient.

In many animals, the geotropism depends on a series of postural reflexes. The "dynamic range" of the sensors involved in geotropism is exhibited by the staphylinid beetle which burrows in sand vertically, and will continue to do so despite a rotation of his original burrow through 70°.

SIMILAR EXAMPLES:

Negative geotropism is displayed by such animals as pulmonate snails, crabs, beetles, and young rats. When these animals are placed on an inclined plane in air they choose a direction of ascent which deviates from the horizontal by an angle theta, which is related to the angle of inclination of the plane, alpha. For many kinds of animals the angle of orientation up the plane varies as the logarithm of the sine of alpha; the pull of gravity on an inclined plane varies as the sine of alpha.

In plants, the roots of seedlings first exhibit positive geotropism by growing downward and later show negative geotropism by growing upward.

GEOTROPISM, Continued:

SAMPLE PHYSICAL ANALOGS:

Perhaps the best physical analog is the Schuler-tuned stable platform used in guidance systems. Once such a platform is oriented along the local vertical, it remains so oriented despite translational motion of the platform.

Vertical-indicating devices are essential to geodesy and civil engineering. The plumb bob and spirit level are familiar everyday tools for determining the local vertical, which for most purposes is adequately defined as the direction of the gravitational gradient.

A system of three mutually-orthogonal accelerometers is somewhat analogous because it provides the direction of the apparent gravity as well as its magnitude despite arbitrary orientation of the sensors.

REFERENCES: 13, pp. 529-542; 116, p. 296.

Physical Class	Physical Operator	Section 5
Fluid Mechanics Mechanics	Sensors Internal	Equilibrium Sensing and Control

SEMICIRCULAR CANALS

DESCRIPTION:

The three semicircular canals in the ears of vertebrates are placed at approximately right angles to each other in three planes and are filled with fluid called endolymph. At the end of each canal is a bulbar enlargement called the ampulla, which is considered a static sense organ. The three ampullae respond to the stimuli of differential pressure and, because of their extreme sensitivity, they are anatomically protected by having the semicircular canals buried deep in the temporal bone, the densest bone in the skull.

A group of delicate receptor cells, with stiff hairs attached, projects into the fluid-filled ampulla cavity, and then connects with the vestibular branch of the 8th cranial nerve. This forms a device which receives stimuli from the movement of the endolymph in the tubes.

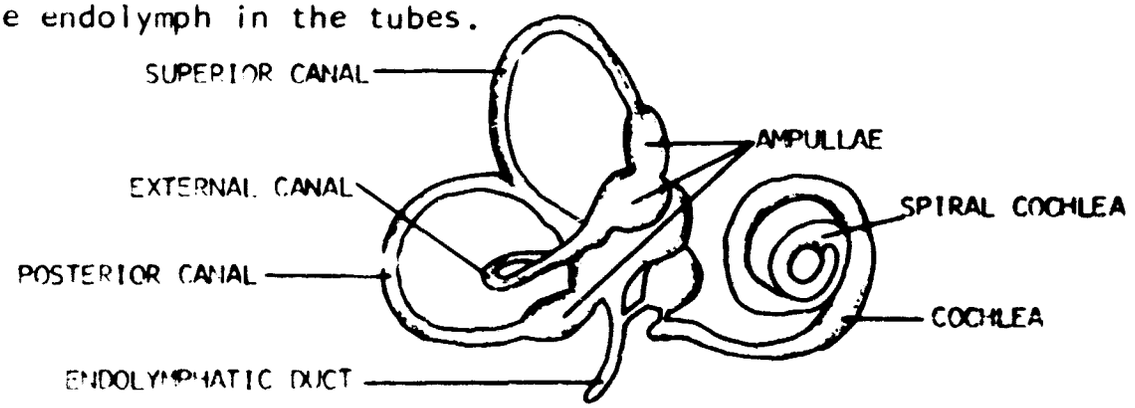

FIG. 8 SEMICIRCULAR CANALS

ILLUSTRATION:

The semicircular canals respond to any one of the following forms of stimulation:

a. Rotation of the head about a vertical, transverse or anteroposterior axis,
b. Artificial mechanical stimulation,
c. Caloric irrigation of the ear with hot or cold water,
d. Galvanic stimulation.

The three semicircular canals are arranged in planes approximately at right angles to one another, functioning with movements in the three dimensions.

The position of the cupula is influenced by an increase or decrease of velocity of rotation, i.e., by positive or negative angular acceleration, but is not influenced by linear acceleration. Any changes in rotation speed cause a deflection of

SEMICIRCULAR CANALS, Continued:

the endolymph with a resulting differential push and pull upon the hairs. Inertia causes the endolymph of the involved pair of canals to lag behind the progress of the wall of its containing tube and therefore to move opposite to the direction of turning.

On irrigating the external auditory meatus with hot and cold water, labyrinthal reactions appear because convection currents are provoked in the endolymph of that semicircular canal which is placed in a vertical position, and changes in the pressure on the ampulla cause the cupula to bend. The direction of the convection currents depends upon changes in the specific gravity of the endolymph resulting from heating or cooling. Irrigating the ear with cold water directs current toward the ampulla of a vertical semicircular canal. When irrigated with warm water, the endolymph rises.

Application of direct or alternating current to the ear also elicits reflexes from the laybrinth. Galvanic polarization produces impulse discharges similar to those occurring on natural rotatory stimulation.

MAGNITUDE:

The semicircular canals vary from 15 to 22 mm in length, the posterior being the longest and the lateral the shortest. The internal width of the bony canals averages about 0.8 mm.

SIMILAR EXAMPLES:

The hagfish, Myxine, has one semicircular canal with an ampulla at each end.

The lamprey, Petromyzon, has two semicircular canals.

Defective statoreceptors (semicircular canals) seem to cause the peculiar exotic circling movements characteristic of the Japanese waltzing mice.

The statocyst of the crayfish (described elsewhere in this section) is a cruder device with comparable function.

Acceleration also compresses body tissues, yielding a sense of acceleration derived from pressure-sending cells.

See, in addition, "Balance and Flight of Insects" in this section.

SAMPLE PHYSICAL ANALOGS:

Although angular accelerometers, plumb bobs, etc., are used to sense accelerations around some center none of these devices functions in quite the same manner. However, there is a satellite orientation controlling mechanism which works in a manner similar to that of the semicircular canal. It consists of three circular canals placed in three mutually-perpendicular directions. As a correction is desired around either axis, a liquid is pumped into the "canal" surrounding that axis in the opposite direction to the desirable correction direction. The vehicle is then oriented in the direction opposite to the direction of the liquid flow. Although this is not a sensing function but an actuator, it is similar physically.

SEMICIRCULAR CANALS, Continued:

REFERENCES: 44, pp. 1140-1144; 96, pp. 133-134.

Physical Class	Physical Operator	Section 5
Mechanics	Sensors Internal	Equilibrium Sensing and Control

STATOCYSTS OF CRAYFISH

DESCRIPTION:

The equilibrium organs of the crayfish are chitinous-walled sacs, called statocysts, situated at the base of each of the antennules. Inside each sac, at its base, are ridges called sensory cushions, each cushion having a set of three hairs. There are 70 to 75 sensory cushions, making a total of over 200 hairs in the statocyst. Each sensory cushion is supplied with its own nerve fiber.

The statoliths are large grains of sand placed between the hairs. Contact of statoliths with statocyst hairs provides information to regulate orientation of the crayfish while swimming.

The special glands beneath the sensory cushion secrete a substance that attaches the statoliths to the hairs. Gravity causes the grains of sand to exert various forces on the hairs, depending upon orientation of the statocyst.

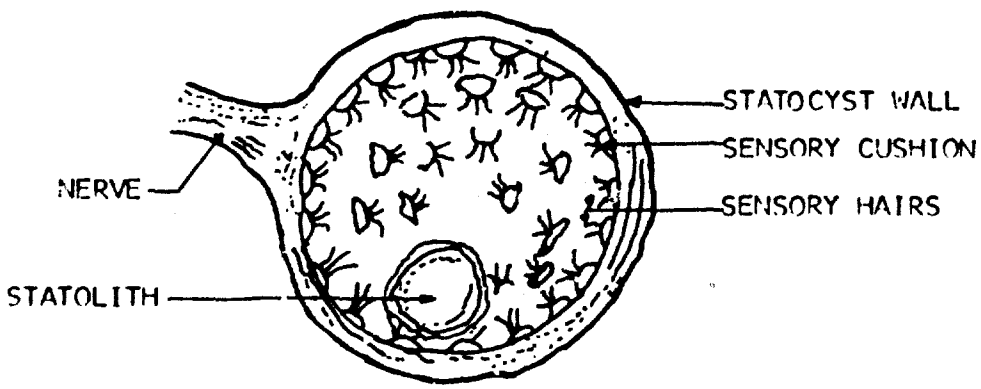

FIG. 9 CRAYFISH STATOCYST

ILLUSTRATION:

The crayfish is always in a state of unstable equilibrium, maintaining its normal position by its own efforts, since the force of gravity tends to turn it over. Any change in position of the animal causes a change in position of the statoliths, which are influenced by gravity. Observations during molting of the crayfish show that the exoskeleton is shed gradually, and the statocysts are removed or lost. This causes the crayfish to lose much of its orientation ability. However, as the exoskeleton grows back, the statocysts and statoliths are replaced.

The basic mechanism of excitation appears to be similar in all statocysts. The hair cells of the ampulla of the horizontal canals show graded depolarization on rotational acceleration toward the ampulla, repolarization on deceleration, and hyperpolarization on acceleration in the opposite direction. These

STATOCYSTS OF CRAYFISH, Continued:

graded depolarizations and hyperpolarizations are generator potentials similar to those of other mechanoreceptors, and they presumably stimulate firing of nerve impulses.

MAGNITUDE:

The frequency of impulses in single statocyst nerve fibers is maximum when the crayfish has its body at an angle of 96° to 120° about the transverse axis. Displacement responses of the statocyst hairs consist of increases or decreases in impulse frequency. The hairs have shown proportional acceleration responses up to 6° to 9°/sec².

SIMILAR EXAMPLES:

In the terrestrial snail there are 2 similar organs of equilibrium, one on each side of the supraesophageal ganglia; these are minute vesicles containing fluid in which are suspended small calcareous statoliths.

In the squid, the 2 statocysts lie side-by-side in the head and may be considered organs of equilibrium in view of their function.

In the fresh-water mussel (Anodonta) the statocysts are located a short distance behind the pedal ganglia. These are small vesicles containing a calcareous concentration similar to the statoliths.

The oblique downward course of shrimp swimming from the surface has been measured under gravity variations by slow centrifugation. The shrimp change swimming direction in such a way that the statocyst excitation remains constant. The angle of descent can be changed by varying the apparent gravity or by removing one statocyst. If both statocysts are removed, centrifugation is without effect.

When a jellyfish is tilted, the lower portion of the mantle contracts more strongly than the upper portion and the animal thereby rights itself. Removal of several of the statocysts causes disorientation.

In the Scyphomedusae (Coelenterates), there are 8 tentaculocysts, each one lying between the marginal lapels. Their function is to aid the medusan body to maintain a state of equilibrium.

In the hydromedusae, the small outgrowths located between the tentacles are similar in appearance and may be considered the same type of organ of equilibrium as the tentaculocysts.

SAMPLE PHYSICAL ANALOGS:

An angular accelerometer is analogous in its function but quite different physically. When the accelerometer is rotated about its sensitive axis and indication of the angular rate of change in velocity is obtained, this indication is usually in the form of an electrical signal proportional to the acceleration. Integrating versions using the same basic principle have been

STATOCYSTS OF CRAYFISH, Continued:

developed to sense angular velocity and angular displacement. The bubble level (or spirit level) is used to obtain a measure of angular displacement from the horizontal.

REFERENCES: 58, p. 361; 116, pp. 299-300.

Physical Class	Physical Operator	Section 5
Fluid Mechanics	Sensors: Contact Actuators: External, Internal	Equilibrium Sensing and Control

SWIM BLADDER IN FISH

DESCRIPTION:

The swim bladder, which is a hydrostatic organ, lies between the alimentary canal and the kidneys in most fish. It may be single- or multi-chambered, and is generally a tough sac overlaid by a capillary network, under which is the tunica externa of connective tissue. Beneath this is the tunica interna composed of smooth muscle fiber with inner epithelial gas-glands. This organ, in general, is specialized anteriorly for gas secretion and posteriorly for gas absorption.

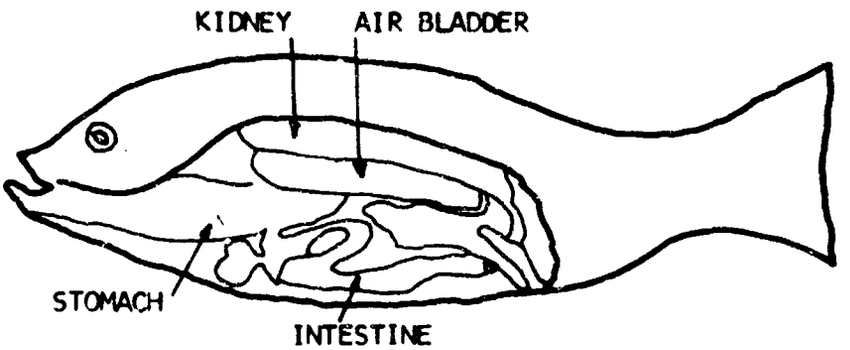

FIG. 10 SWIM BLADDER IN FISH

ILLUSTRATION:

The primary function of the swim bladder is to keep the fish at the same specific gravity as the water. The specific gravity of the fish, rising or falling because of the increase or decrease of pressure at various depths as it descends or ascends, causes a greater or lesser compression of the gases in the swim bladder.

By altering the internal pressure and volume of the swim bladder a fish can remain in hydrostatic equilibrium with the changing water pressure and thus is able to move up or down with a minimum of muscular effort.

MAGNITUDE:

In those fish with bodies of densities near that of water, the swim bladder volume is about 5% of the body. This is less in marine fish (e.g., Physoclist), which do not have a pneumatic duct connecting the air bladder to the alimentary canal, than in fresh water fish.

SIMILAR EXAMPLES:

The fish, Hippocampus, has a double swim bladder made up

SWIM BLADDER IN FISH, Continued:

of both an anterior and a posterior chamber. When this fish moves from a resting place, its movement is compensated for by the expansion of the posterior chamber.

SAMPLE PHYSICAL ANALOGS:

Submarine ballast tanks serve an identical purpose. As air is pumped from the ballast tank and is compressed and stored or released (blown), water replaces the air. The ship's bouyancy is decreased causing it to submerge. Surface vessels also use ballast tanks to adjust their bouyancy to compensate for unevenly distributed cargo.

Lighter-than-air craft (balloons, dirigibles) adjust their volume to balance weight with the weight of the air displaced to achieve a desired altitude.

REFERENCES: 113, pp. 339-342; 116, p. 189.

Physical Class	Physical Operator	Section 5
Fluid Mechanics Mechanics	Sensors Actuators Internal External	Equilibrium Sensing and Control

TYPES OF EQUILIBRIUM

1. Indifferent Equilibrium

DESCRIPTION:

Indifferent equilibrium involves no specific sensors and usually implies no definite orientation with respect to gravity. It is also called "neutral" equilibrium.

ILLUSTRATION:

Indifferent equilibrium is best illustrated in microscopic organisms, such as the heliozoans, which are spherical microscopic protozoa that hang suspended, any side up, without contact with solid objects.

SIMILAR EXAMPLES:

A similar example is the green, globular colonies of Volvox, which roll around in pond water without any visible orientation preference.

SAMPLE PHYSICAL ANALOGS:

Any physical device which does not depend upon an appropriate alignment of gravitational force for its operation can be said to share this property with heliozoans but not necessarily to be analogs. Many devices fall in this category, including transistors, vacuum tubes, pumps, motors, etc.

2. Stable Equilibrium

DESCRIPTION:

This type of equilibrium does not depend on special sense organs. It applies not only to inert forms but also to living bodies. The force of gravity acts on the animal and allows it to come to rest without muscular effort.

ILLUSTRATION:

Stable equilibrium is exhibited in the flounder which is able to come to a resting position on one side while in the water.

The eggs of the nighthawk, which are laid on sloping rocks, have evolved into a watch-shaped form which prevents them from rolling.

SIMILAR EXAMPLES:

The spreading legs of spiders provide stable equilibrium. Some forms of passive homeostasis, such as buffering of the

TYPES OF EQUILIBRIUM, Continued:

acidity of the blood, are also examples of stable equilibrium.

SAMPLE PHYSICAL ANALOGS:

The term stable equilibrium also applies equally well to inanimate objects as to animate objects. There are no analogs, per se, for living systems in this condition.

3. Labile Equilibrium

DESCRIPTION:

This type of equilibrium is in effect when the center of gravity of a body is too high in relation to restoring torques, to allow balancing without muscular effort. This involves many biological factors in the body as well as involving the external physical force of gravity. First, a tension must be maintained between opposing muscles to prevent collapse. Second, the coordinating nervous apparatus, utilizing information from the pertinent sense receptors, must cause the muscles to suitably stabilize the body of the organism in its specific environment. Labile equilibrium is also called "unstable equilibrium".

ILLUSTRATION:

In man, the upright position is maintained by the use of several sense organs, listed here, which are mainly related to other purposes:

a. Touch receptors, on the soles of the feet in contact with the ground, which act as stereotactic pressure organs.

b. Sense of sight, which informs man of his position in his surroundings.

c. Nerve endings from the acoustic nerve (8th cranial) connect with the semicircular canals of the ears, which have a gravity sensing function similar to the statoreceptors in the invertebrate animals.

d. Proprioceptive "muscle sense" assures the proper tension of the opposing muscles.

SIMILAR EXAMPLES:

A crane standing on one leg is kept in an upright position by the action of sensory, controller and muscular systems.

SAMPLE PHYSICAL ANALOGS:

Since the term labile equilibrium applies to systems that are maintained in equilibrium by a control system with suitable sensors and actuators, it is clear that a flight control system or a temperature regulation system is an analog of a living system in that it performs all the functions of regulation.

REFERENCES: 144, p. 786.

SECTION 6:

LEARNING

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BIOLOGICAL ASPECTS OF LEARNING

Perhaps the most generally accepted and widely applicable definition of learning is the operational one which states that learning refers to a more or less permanent change in behavior as a result of reinforced practice. In this way, such factors as maturation or physiological variables of themselves are excluded, effects of adaptation or fatigue are eliminated, and learning is identified as an intervening variable. However, the factors involved, that is, behavioral change, reinforcement and practice, are directly observable and verifiable.

There are essentially two types of learning: (1) the Pavlovian or classical conditioning and (2) instrumental or operant conditioning as discussed by B. F. Skinner. The main differences lie in the nature of stimuli and reinforcements. Classical conditioning effects a relationship between the unconditioned stimulus which evokes the response initially, and the conditioned stimulus such that the latter will evoke the response peculiar to the former.

In the instrumental type of learning, the critical tie is between the (unconditioned) stimulus and the response. The purpose here is to elicit a particular piece of behavior upon the stimulus presentation. It is the establishment of this stimulus-response bond which is important. In addition, operant reinforcement is applied after the response is obtained and serves to increase the probability of the occurrence of that response in the future.

Using this conception of learning, employing no mentalistic terms, we are able to say that animals learn in the same sense as man learns. Both employ a trial and error process. Man, of course, can progress in a faster and more complex manner because of his superior reasoning abilities. Similarly, whereas the reinforcement situation for an animal is straightforward and controllable, an effective reward for man may be quite complex. Such factors as personality, motivation, and attitude may influence his performance in unknown quantities.

For this reason animals are widely used in experimental investigations. Nevertheless, despite complexity of the intervening variables, extensive information on learning can be acquired with human subjects.

PHYSICAL ANALOGS IN GENERAL

Data handling systems of the future will be developing from the automatic to the autonomous, that is, toward what has been termed "intelligent" machines, or automata. The best evidence of the type of functions a general-purpose adaptive system or device should possess is provided by observation of living systems. The simpler animal nervous systems are important because we can experiment with them freely, and because their simplicity sometimes facilitates our understanding of the process. In the case of the human brain, we can take advantage of introspection, psychological experiments, data from operations or autopsies, and heuristics. Learning leads to consideration of systems that are goal-directed. Goals may be either predefined or autonomously evolved, or both.

General-purpose automata must be capable of behaving adaptively and intelligently on the basis of raw environmental data. This requirement implies the need for generalized learning, including the ability to learn the significance of sensor data from a multiplicity of sensors. In addition, analyzed data must be integrated to provide a basis for action within the constraints of the automaton goals and effectors. The effectors, such as manipulators, locomotors, and communicators, must be fairly general to provide scope for adaptation to a wide range of environments. Generalized learning in machines must encompass perception, autonomous decision-making, and action; it should be able to cope with unforeseen circumstances, finding means whereby the machines can solve problems without being provided with specific a priori information.

Learning, combined with a suitable mechanism for searching function space, can provide this capability in machines, by a trial and error process similar to the natural selection of species. Learning, in fact, is a form of natural selection of functions. A learning machine may be composed of adaptive artificial nerve cells (neuromimes), for example, Probability State Variable devices, linked in a random or systematic manner. These devices employ a random search of function space, modified by previous learning. Other devices employ a systematic search of function space (Ref. 86). The random search function may be preferable because it provides a simple way of avoiding cyclic repetitions of useless behavior, it emancipates the machine from the limitations of the designer (up to the limit of functional capability of the machine), and it can provide a possibility of trying all points in function space over a continuous range. Deterministic search functions appear applicable where considerable a priori knowledge is available concerning the problems to be encountered by the machine. The type of search function depends on the kind of information the designer may possess regarding the problems to be encountered by the machine. This is a

central consideration in the learning theory of men and machines.

Generalized learning involves the search of function space, as well as the selection of satisfactory functions that have been found. Two very good terms for describing this process have been discussed by D. T. Campbell; they are "blind variation" and "selective survival" (Ref. 41). The learning must be step-by-step, involving multistability, if complex functions are to be developed (Ref. 3).

Physical Class	Physical Operator	Section 6
Acoustics Chemistry Electricity and Magnetism Mechanics	Sensors: Contact, Distance, Internal Actuators: External, Internal	Learning

CHAIN OF CONDITIONED REFLEXES

DESCRIPTION:

Once a conditioned stimulus has become effective for a desired reaction, it can be used as the stimulus for the development of a second conditioning without recourse to the original adequate stimulus. This is known as "secondary conditioning" and might be described as a chain of conditioned reflexes.

ILLUSTRATION:

If electric shock is applied as the unconditioned stimulus for leg withdrawal and a tone is presented before the shock, then the tone becomes the conditioned stimulus for the withdrawal response. If the shock is omitted and a light is presented before the tone, it will acquire stimulus properties so that the onset of the light alone will result in flexion of the leg. Thus, the tone has assumed the characteristics of the unconditioned stimulus and the light, the conditioned stimulus.

MAGNITUDE:

Some experiments have reported the establishment of response chains up to 5 consecutive sequences; however, these are difficult to obtain and highly unstable.

SIMILAR EXAMPLES:

Wolfe performed experiments with instrumental conditioning in which chimpanzees were trained to insert poker chips into a food-vending machine to get food. This was first-order conditioning with food as the primary reinforcement. The animals were then trained to lift a bar to obtain these chips. The reinforcement value of the chips was measured by an obstruction task, i.e. the chimps would lift the bar against considerable resistance to obtain the poker chips. Further experimentation made use of this fact by using the chips as rewards for the correct response in a discrimination task. Here, the primary reinforcement consisted of the poker chips themselves, since food was no longer introduced.

SAMPLE PHYSICAL ANALOGS:

Consider a plastic neuron having at least three input variables, A, B, C, with synaptic weights, a_1, a_2, a_3, respectively, and a threshold T. Let weight, a_i, increase if and only if the neuron fires when the i^{th} input was active (for any i). Let the initial values of a_1, a_2, a_3, be related to T by:

CHAIN REFLEX, Continued:

$$a_1 \geq T$$

$$a_2 < T$$

$$a_3 < T$$

Throughout the procedure, T will remain fixed. Signal A is the analog of the unconditioned stimulus, the neuron output being "one" for this input only. B is the first conditioned stimulus and is presented simultaneously with A until $a_2 > T$, when the neuron function becomes $F = A \cup B$. B alone will now cause firing and can now be used to condition a response to C, in like manner.

REFERENCES: 85, pp. 165-167; 116, p. 645; 149, p. 681.

Physical Class	Physical Operator	Section 6
Chemistry Electricity and Magnetism	Transformers Information	Learning

CONDITIONED REFLEX

DESCRIPTION:

I. P. Pavlov demonstrated a type of conditioning whereby, with repeated pairing of a theretofore neutral stimulus with one which dependably ("reflexly") evoked a given response, the former would then produce a response peculiar to the latter.

ILLUSTRATION:

The referenced experiment involved the salivation of the dog. The neutral stimulus, ringing of a bell, was consistently presented a few seconds prior to the unconditional stimulus, meat. After several pairings, the bell alone evoked the same response as the meat, namely, salivation. Further analysis has shown that the conditioned response (salivation to the bell) may differ from the unconditioned response (salivation to the meat) in magnitude and/or composition, but they are so similar as to be readily identifiable.

Pavlov explained this conditioning effect on the basis of neural centers of excitation. Essentially, he stated that a neural pathway existed between the unconditioned stimulus center and the response center. Conditioning, he maintained, involved the establishment of a pathway between the conditioned stimulus and the response centers.

Extinction or the loss of a given response was due to the destruction of these pathways. Generalization or the transfer of these stimulus properties to similar but not identical stimuli resulted from an irradiation process. The neural centers were excited, and this excitation would irradiate (spread) to nearby centers so that other stimuli could evoke the same response to a greater or lesser degree.

MAGNITUDE:

The conditioned stimulus is presented between 5 and 10 sec before the unconditioned stimulus. The strength of the conditioned response, as determined by presenting the conditioned stimulus alone for 30 sec, increased with training. After 30 combinations, 60 drops of salivation were measured. On the early tests salivation did not occur until the conditioned stimuli had sounded for 18 sec; on later tests, salivation occurred after only 1 or 2 sec.

SIMILAR EXAMPLES:

This type of conditioning may take place in the individual neuron. Related topics are discussed under "Nerve Sensitivity".

See other entries in this section for additional information on conditioning.

CONDITIONED REFLEX, Continued:

SAMPLE PHYSICAL ANALOGS:

See Sample Physical Analogs under entry on "Chain of Conditioned Reflexes".

REFERENCES: 78. p. 45; 110, p. 15.

Physical Class	Physical Operator	Section 6
Chemistry Optics and Light	Sensors Distance Transformers Information	Learning

IMPRINTING IN ANIMALS

DESCRIPTION:

Imprinting is the phenomenon in which an experience at a critical period during the early development of an animal determines his future social behavior. This has been studied mostly in birds although it is also known to occur in insects, fish, and some mammals.

The fact that such characteristic properties as acquisition and generalization apply meaningfully to this type of behavior suggests a close relationship between it and other types of learning.

ILLUSTRATION:

A series of experiments by E. H. Hess tested the effect of imprinting on mallard ducks. The ducklings were kept in isolation until the imprinting session was to occur. At that time, the herd was placed on a runway about a foot away from a motor-driven decoy. Experiments varied so that some decoys were silent whereas others emitted a sound similar to the quacking noise of a duck. During the imprinting period, the duckling would normally follow the decoy around the runway. The testing was done by releasing the bird between two decoys, the one originally used for training, and another, differing perhaps only in coloration or sound emission. Results showed that the duckling consistently followed the original decoy.

Moreover, the orienting figure does not necessarily have to be of the same species. Experiments have been performed in which the duckling has been imprinted to follow the experimenter rather than a decoy. Similarly an inanimate object such as a ping-pong ball or box will be followed if it was the first object seen by the animal.

MAGNITUDE:

Those ducklings which had to climb over obstacles or go up an inclining rather than a flat runway showed a greater degree of imprinting such that the following definition was suggested: the strength of imprinting equals the logarithm of the effort expended by the animal during the imprinting period.

Maximum scores are obtained with birds which are imprinted between 13 and 16 hours after hatching. The length of the imprinting period seems to be of little importance.

SIMILAR EXAMPLES:

Imprinting may involve the sense of smell as well as the sense of sight. This fact is obvious in the homing behavior of salmon which will return to original waters to spawn. The

IMPRINTING IN ANIMALS, Continued:

determining factor here is the characteristic odor of the water which is imprinted in the fish. For further details see "Homing Migration of Salmon".

SAMPLE PHYSICAL ANALOGS:

Imprinting resembles the type of learning in machines that is sometimes called "one-shot" learning or "freeze"-learning in which the learning system is frozen in function after a single, successful attempt to solve one problem of a large class of problems. Other problems in the same class may not be suited to the particular solution found, but this is not relevant to the description of freeze-learning.

REFERENCES: 62, pp. 81-90; 129, p. 90.

Physical Class	Physical Operator	Section 6
Chemistry Electricity and Magnetism	Transformers Information	Learning

INSTRUMENTAL CONDITIONING

DESCRIPTION:

The type of conditioning which most closely resembles normal everyday activity is instrumental or operant conditioning. This refers to the situation in which a stimulus is presented and the reinforcement or reward is not given until the correct response is made. The reinforcement then is contingent upon the subject's actions, not those of the experimenter.

ILLUSTRATION:

An experimental example of this type of conditioning would be the following:

An animal is placed in an apparatus such as the Skinner box. This apparatus may contain a lever, a food hopper and two areas for stimulus presentation. The task may be to press the lever only in the presence of light; that is, both areas must be illuminated for a response to be correct. If the animal is successful in discriminating this situation, he is rewarded by a pellet from the food hopper. The animal will learn very quickly to differentiate between the light on-light off situation and respond accordingly.

Such theories as drive reduction and simple contiguity have been suggested to account for the effectiveness of the reinforcement.

MAGNITUDE:

The frequency and duration of reinforcement has much influence on the rate of responding. A stronger response, one which takes longer to extinguish, is achieved with intermittent reinforcement such as one reinforcement every two minutes or one every 25 responses. During one experiment with a pigeon required to peck at a key for the correct response, with only one reinforcement every 10 minutes, the bird pecked the key 25 times a minute for the entire 10 minute interval.

SIMILAR EXAMPLES:

The process of instrumental conditioning is very similar to the manner in which man establishes habits. In any particular situation, he may try several fruitless actions. Eventually one act will be the "right" one and therefore, in some manner, be reinforced. Several confrontations with the same or similar situations will lead to the establishment of this stimulus-response chain as a completely habitual action.

SAMPLE PHYSICAL ANALOGS:

The Neurotron learns in a manner closely resembling

INSTRUMENTAL CONDITIONING, Continued:

instrumental conditioning under normal circumstances. An input (or set of inputs) is applied to the Neurotron and a reward (reinforcement) signal is supplied to the Neurotron if the response is correct. For incorrect responses, a punishment (non-reinforcing) signal is supplied. Eventually, the reward and punishment signals condition the Neurotron to favor a particular function over others.

Generalized learning is incorporated into the Neurotron by a goal circuit which determines whether to reward or punish the Neurotron on the basis of either a built-in or a learned criterion.

REFERENCES: 40, pp. 437-450; 72, pp. 811-867; 110, pp. 57-62; 149, p. 563.

SECTION 7:

LIGHT PRODUCTION

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BIOLOGICAL ASPECTS OF LIGHT PRODUCTION

The ability of living organisms to produce light is called bioluminescence. In all cases, the light is a result of a chemical reaction in which the molecules of the light producing compound called luciferin are acted upon by the enzyme luciferase in the presence of oxygen. A survey of the animal kingdom discloses at least 40 orders containing one or more forms known to produce light. In the plant kingdom the luminous forms are the bacteria and fungi. Luminous animals are practically all either marine or terrestrial. Not only the adults but the embryos and the eggs of some animals are luminous.

We may divide luminous organisms into two classes, intracellular and extracellular, according to whether the oxidizable material is burned within the cell where it is formed or is secreted to the exterior and is burned outside. In the higher forms the eye contains groups of photosensitive rods and cones connected with afferent nerves, lenses, and accessory structures for properly adjusting the light; luminous organs contain groups of photogenic cells in connection with efferent nerves, lenses and accessory structures for properly directing the light. Many errors have resulted from attempts to infer luminescence in an animal by study of preserved material. For example, many nonluminous animals may become infected with luminous bacteria. Fish are the highest group of animals in which self-luminosity is known. All reported cases of light from Amphibia, reptiles, birds, and mammals have been due to some secondary phenomenon.

PHYSICAL ANALOGS IN GENERAL

Light can be produced by a wide variety of physical and chemical means. Fire, incandescence, and fluorescence are well known. In incandescence, atoms of materials are raised to an excited state by collisions and light is emitted when the atoms drop back to a lower energy state. The light emitted by a flame is due to the incandescent gases. Fluorescence is a re-emission of light; certain phosphors will emit visible light when bombarded by ultraviolet light. Other phosphors can be excited by bombardment with electrons and produce light when they return to a lower energy state. Still other phosphors emit light when placed in an electric field (electroluminescence).

Less well-known methods of light production include the production of light by friction, by heat (thermoluminescence,

which is not the same as incandescence), and by bombarding a dielectric material with particles traveling faster than the velocity of light in the dielectric; this latter method produces a blue light called Cerenkov radiation.

Electrochemical methods of light production have been studied for their efficiency. For example, a solution of aluminum citrate will produce a white light if two electrodes with a sufficient potential difference are placed in the solution. Purely chemical methods of producing light involving chemicals such as luciferin and luciferase are also known.

Most of the older methods of light production are relatively inefficient when compared to chemical methods. However, some of the newer methods, such as the production of infrared light by a semiconductor junction, approach 100% efficiency in the conversion of energy into light.

Physical Class	Physical Operator	Section 7
Chemistry Heat and Thermodynamics Optics and Light	Transformers Actuators Energy Internal	Light Production

BACTERIAL LUMINESCENCE

DESCRIPTION:

Light production by bacteria is the result of an oxidation reaction between a chemical known as luciferin and an enzyme called luciferase. Generally speaking, luminescent bacteria make up a physiologically related group which differ in their morphological characteristics. Most of these luminescent bacteria are found in the sea or are derived either directly or indirectly from animal life which has been in the sea. Although their natural habitat and food requirements are on bodies of fish and other types of meat, they are not putrefactive in any way, but some of the pure cultures produce a noticeable odor. These luminescent bacteria, of which an example is Achromobacter fischeri require a relatively high concentration of sodium chloride, usually about 3% in the growth medium. Growth temperature is an important factor; the optimum temperature for both the growth and luminescence of these bacteria is in the range of 15 to 20°C.

ILLUSTRATION:

Bacterial luminescence remains constant over considerable periods of time in nonreproducing cells under favorable conditions. The light-emitting system is in a steady state, reduced luciferin being regenerated at the same rate it is being oxluized.

The luminescent system of bacteria appears to be indissociably bound to intact, living cells. Osmotic cytolysis, mechanical grinding, sonic vibration, catalytic agents, all destroy the capacity for luminescence along with the viability of the cell.

The rate of the reaction of bacterial luminescence depends upon the equilibrium between the molecules that are in the normal state and in the activated complex. The exact notion of the activated complex itself is based on statistical mechanics. When once formed, the activated complex decomposes with a universal frequency which is the same for all light emission reactions, and is given by the expression

$$k\frac{KT}{h}$$

in which k is the transmission coefficient, representing the probability that the formation of the activated complex will lead to its decomposition into the products of the reaction, rather than a reconstitution of the reactants. K is the Boltzmann constant (1.372×10^{-16} erg/degree), T is the absolute temperature and h is Planck's constant (6.547×10^{-27} erg-second). For most light emission reactions, the value of k is very close to 1.

BACTERIAL LUMINESCENCE, Continued:

MAGNITUDE:

The intensity of the luminescence at any moment is proportional to the concentration of the enzyme times that of the substrate. Although the peak intensity for light emission in the bacteria is in the blue or blue-green region of the spectrum, there is light emitted over the range of approximately 400 to 650 mμ. However, since the major spectral emission is around 480-490 mμ, the light is blue or blue-green in color.

SIMILAR EXAMPLES:

The production of light by living organisms, also called bioluminescence, has been seen in all major groups of animals from protozoa through the chordates. Another example, chemical in nature, concerns the pressure-temperature relationship of the activity of yeast invertase in crude extracts. This shows similarities to the chemical principle of luminescence in living bacteria.

SAMPLE PHYSICAL ANALOGS:

Production of light by chemical means (chemiluminescence) is not merely analogous to bioluminescence, it is the process which underlies it. Physical means for light production also include fluorescence, phosphorescence, thermoluminescence and incandescence.

REFERENCES: 52, pp. 327-482; 99, p. 3; 100, p. 177; 116, p. 495.

Physical Class	Physical Operator	Section 7
Chemistry Optics and Light	Transformers Actuators Energy Internal	Light Production

CYPRIDINA LUMINESCENCE

DESCRIPTION:

There is a small crustacean of the ostracod type called Cypridina hilgendorfii, which has a large luminous glandular organ located in its head region near the mouth. Within this gland are two distinctly different types of cells. One produces the luminescent chemical luciferin in the form of yellowish granules. The other kind of cell produces the enzyme, luciferase, also in granular form, but colorless, and somewhat smaller in size than the luciferin granules. The luciferase is forced by muscular action through two separate pores. When granules of luciferin and luciferase mix outside of the body in the presence of oxygen, the reaction produces luminescence. This process is controlled by the nervous system. The production of this luminescence is extracelluiar, i.e., it is produced outside of the cells that produce the chemical, and in this particular example, entirely outside the body of the organism.

ILLUSTRATION:

The light emission of Cypridina is a chemiluminescence which consists of a short band of wavelengths in the green or blue region of the visible spectrum.

When dried, Cypridina can be stored almost indefinitely, only to become brilliantly luminous again when wet, even after more than 20 years. The reaction is not essentially a "living" reaction, insofar as it survives the death of the organism. In itself it is not dependent upon living cells, although they are necessary in the stages of preparation. On the other hand, oxygen is necessary, although only in a small amount.

MAGNITUDE:

Visible light is emitted on oxidation of 0.00001 μg/ml (2×10^{-11} molar) of Cypridina luciferin with 0.01 μg/ml of luciferase protein, or with 1 μg/ml of luciferin with 0.0000001 μg/ml (2×10^{-16} molar) of luciferase. Data on yields indicates the average content of luciferin and luciferase to be about 1 μg of each in a single living organism.

SIMILAR EXAMPLES:

The luminescence produced by both the bacterium Achromobacter fischeri and the firefly Photinus is considered to be intracellular, since the oxidation reaction that produces the light takes place within the cells.

SAMPLE PHYSICAL ANALOGS:

Zinc Sulfide (ZnS) and Zinc Oxide (ZnO) mixtures produce

CYPRIDINA LUMINESCENCE, Continued:

light as do other chemicals.

REFERENCES: 53, pp. 171-187; 71, pp. 1755-1756.

Physical Class	Physical Operator	Section 7
Chemistry Optics and Light	Transformers Actuators Energy Internal	Light Production

FIREFLY LUMINESCENCE

DESCRIPTION:

Luminescence is produced by the firefly (lightning bug) from the fourth and fifth segments of its abdominal region. It is in this region that the enzyme luciferase and the chemical luciferin react to produce light.

The light producing organ is composed of two cellular layers, a ventral layer of light-producing cells and a dorsal or internal layer of "reflecting" cells.

ILLUSTRATION:

The chemical reaction producing luminescence in the firefly is controlled by the nervous system. A direct nervous excitation of the light-producing cells releases oxygen into the tracheal end cells permitting the oxidation of luciferin, catalyzed by the enzyme luciferase.

MAGNITUDE:

The light produced by the firefly is cold light. It has an efficiency between 92 and 100%. In comparison, illuminating gas light has only a 3% efficiency, an incandescent lamp about 10% and [illegible]light a 25% efficiency.

SIMILAR EXAMPLES:

The carbuncle beetle of Puerto Rico produces one of the brightest types of animal luminescence known. One or two of these beetles in an inverted drinking glass in a dark room of average size will produce enough light to allow a person to read a newspaper. This luminescence, which appears to be continuous, varies in color from yellow to green with the different species.

SAMPLE PHYSICAL ANALOGS:

Chemiluminescence, i.e., luminescence produced by certain chemical reactions such as the oxidation of magnesium p-bromophenol bromide, is analogous to the light produced by the firefly.

REFERENCES: 36, p. 194; 38, p. 590.

SECTION 8:

LIGHT SENSITIVITY

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LIGHT SENSITIVITY
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BIOLOGICAL ASPECTS OF LIGHT SENSITIVITY

Sensitivity to light is a useful and necessary characteristic of living things. For plants, for example, energy, especially of the longer wavelengths of visible light, is essential to photosynthesis as well as to phototropic behavior necessary for adaptive responses to daily changes. This sensitivity appears to be associated with carotenoids present in plants although the specific pigment is still unknown.

Sensitivity of the general body surface to light exists in species of several phyla of animals, including some fish and amphibians. Similarly, in the echinoderm, there is a diffuse reaction to light. The distribution of skin sensitivity corresponds closely with that of neural elements, indicating a sensitivity of the nerves themselves to light. These dermal chromatophores play a role analogous to that played by the retinal pigments of specialized eyes.

In the more highly developed species of animals, there are specialized organs, or eyes, for photoreception. These may range in degree of development from being able to accurately localize the direction from which light comes (direction eyes), to the ability to differentiate the detailed pattern of light reflection from the complex of objects in the direct field of vision (image-forming eyes).

Vision at high luminosities permits collection of much information and development of elaborate behavior patterns. First, there is the possibility of using great resolving power to discriminate fine detail and small movements, and of taking correspondingly detailed action. Second, the eye and brain together can recognize and react to a great variety of significant patterns and shapes from the changes in the light intensity produced. Third, photopic vision is often associated with a high degree of wavelength discrimination which results in the experience of color vision.

PHYSICAL ANALOGS IN GENERAL

The mechanisms that provide sensitivity to light, color, and optical pattern detection in animals are exceedingly complex and many aspects of these mechanisms remain to be delineated. Some light sensitivity is unquestionably due to the retina, but many aspects of light detection are controlled by neural feedback mechanisms. While color vision also depends upon the existence of certain types of retinal cells, the decoding of color information by the brain is still largely a mystery, although several theories have been advanced on this point. Pattern detection and recognition is somewhat better understood now than it was even a few years ago, through studies of artificial nerve networks and of machine perception in general.

Artificial nerve networks attached to appropriate sensors provide us with the best available physical analog of the visual process. The most general visual analog could be said to consist of a transducer that converts light into suitable signals plus a parameterization or property filtering system. This type of analog is very similar to the analogs of other senses such as hearing and touch.

The entries in this section range from phenomena that involve only part of the visual process to some that, perhaps, involve all of it. From the phylogenetic point of view, the entries range from vision in lower animals to vision in human beings. The physical analogs for these entries also vary in the degree to which they might be said to be analogous to the corresponding physiological or psychological phenomena. In other words, the degree of "realism" of the analogs varies.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance Actuators Internal	Light Sensitivity

ACCOMMODATION

DESCRIPTION:

Accommodation is the process of changing the eye focus by varying the curvature of the eye lens. The latter is brought about by altering the tension on the zonula which is the fibrous ligament extending from the ciliary body to the margin of the lens.

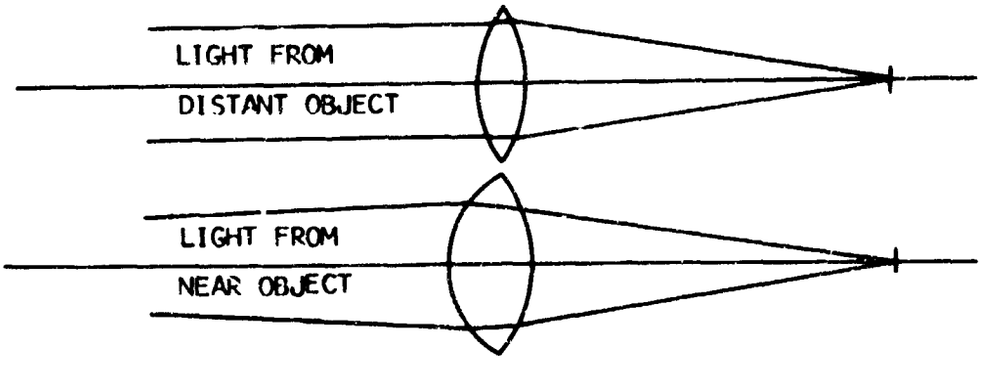


FIG. 11 CHANGE IN LENS CURVATURE DUE TO FOCUS ON OBJECTS AT DIFFERENT DISTANCES

ILLUSTRATION:

When the eye is at rest, the lens is focused for distant objects by a slight tension, or sclerotic stretching, on the lens. It focuses for near objects by contraction of the ciliary muscles in the ciliary body. This narrows the diameter of the ring formed by the ciliary body and allows the lens to round off a little by its own elasticity.

MAGNITUDE:

The refractive power of a lens is expressed as the reciprocal of the focal distance, the unit being 1 m and is called a diopter. The reciprocal of the far point distance is the static refraction, R, of the eye, and that of the near point is the dynamic refraction, P. The difference between the two gives the amplitude of accommodation as equaling P-R. This factor diminishes in man from about 16 diopters at age 12 to about 1 diopter at age 60.

SIMILAR EXAMPLES:

Only a few mammals are able to accommodate. Most birds and reptiles accommodate by squeezing the lens with the ciliary muscles to change the curvature. In fish and amphibians, the lens is moved backward and forward in relation to the retina.

ACCOMMODATION, Continued:

SAMPLE PHYSICAL ANALOGS:

Accomodation (change of lens curvature) does not take place in physical optical systems. The obvious reason is that to change the curvature of a physical lens would require that the lens be made from some flexible transparent material that had precise optical characteristics. The mechanism required to control the curvature would be much more complex than moving the lens to change focus.

Focusing is obtained in some electronic cathode ray tubes by adjusting the magnetic focusing coil strength which has some similarity to accommodation. This adjustment is not made to focus on near and far screens but only to compensate for small changes in physical and electrical properties caused by aging and/or manufacturing deficiencies.

REFERENCES: 7, p. 692; 68, pp. 961-962.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance	Light Sensitivity

AFTERSENSATIONS

DESCRIPTION:

When light is allowed to fall briefly on the retina, the excitation does not cease abruptly with the termination of the stimulus, thus aftersensations are created. Positive aftersensation retains the same qualitative characteristics as the sensation by which it is caused. Negative aftersensation, developing as a final stage of the same process, is of complementary quality. The conditions favorable to the observation of one kind of aftersensation are not the best for the other, although every visual act has potentialities for some type of aftersensation.

ILLUSTRATION:

Positive aftersensations may be formed when a person looks directly at a bright white light for a moment, then closes his eyes or turns toward a dark surface. An image of the light comes into view very slowly, becoming quite distinct for a short time and gradually fading. Negative aftersensations may be formed if, after looking at a bright light or object, the person looks at a sheet of white paper. In this manner the retinas are stimulated a second time, and diffusely, by white. The result is that a dark image is seen against a white background. If the object is brightly colored, an image of the object will appear on the white paper, but its color will be the complement of the color of the object itself. For example, a green object will be seen as red and a blue object will be seen as yellow.

MAGNITUDE:

Viewing a bright red object for a period of 20 seconds is sufficient time to evoke an aftersensation of bluish green.

SIMILAR EXAMPLES:

See entry on "Contrast"

SAMPLE PHYSICAL ANALOGS:

A phenomenon similar to positive afterimage is exhibited by cathode-ray-tube screens due to the persistence of the phosphor coating.

Radar PPI scopes depend on long persistency coatings to retain individual signals while the antenna is scanning the area, receiving information from only a small sector at any one instant.

AFTERSENSATIONS, Continued:

REFERENCES: 7, p. 1372; 37, pp. 63-65.

Physical Class	Physical Operator	Section 8
Acoustics Optics and Light	Sensors Distance	Light Sensitivity

BETZOLD-BRÜCHE EFFECT

DESCRIPTION:

The Betzold-Brüche effect is the change in hue of the spectral colors which accompanies a change in the level of illumination as seen by man.

ILLUSTRATION AND MAGNITUDE:

With the exception of certain invariable points in the spectrum, all colors, when brightened, shift slightly towards either yellow or blue. This effect of shift in hue with changing intensity - the Betzold-Brüche effect - can be quantified by plotting contours of equal hue which describe the combinations of intensity (in photons) and wavelength (in millimicrons) which will yield equal-appearing hues. (See illustration.)

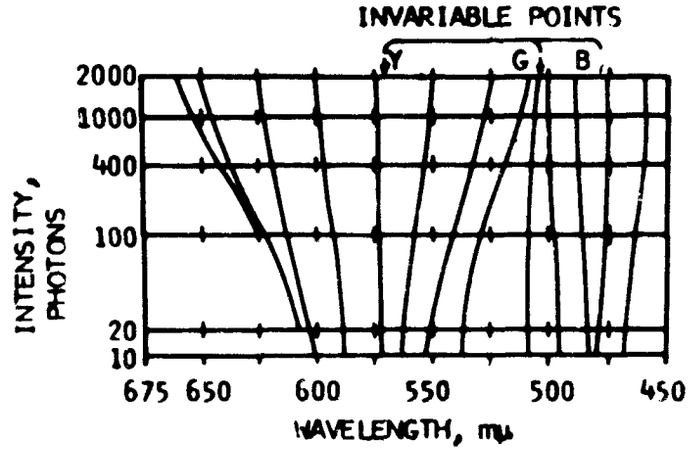


FIG. 12 HUE SHIFT DUE TO BETZOLD-BRÜCHE EFFECT

Only three points within the visible spectrum are invariable, that is, show no shift in apparent hue with changing intensity. These points are yellow at 572 mμ, green at 503 mμ, and blue at 478 mμ. All the other points vary in a predictable fashion according to the Betzold-Bruche effect.

SIMILAR EXAMPLES:

In audition, perceived pitch is easily identified with frequency, and loudness with intensity of sound waves. For pure tone one finds an analog of the Betzold-Brüche effect since perceived pitch changes as intensity is changed even though low frequency tones, when raised in intensity, sound lower in pitch,

BETZOLD-BRÜCHE EFFECT, Continued:

while high-frequency tones sound higher in pitch when their intensity increases.

SAMPLE PHYSICAL ANALOGS:

Color film when improperly exposed will show a similar effect. Color balance is maintained only throughout a small range of illumination. When either more or less than the desired illumination is allowed to expose the film, certain dyes will predominate giving a distorted color mixture. In film, the apparent shift of color with intensity is partly due to different response times of the dyes. Dyes deviate from a true proportional dependency of the integral of light flux with respect to time.

An automatic frequency control circuit shifts frequency as a function of amplitude but this is a real frequency, or response, shift and not an apparent one.

Simple spring mass systems, although normally assumed linear, will have a response dependency on amplitude when complex inputs are provided.

Many crystals, used as filters or oscillators, will exhibit a response depending to some degree on amplitude. Such dependency is attributed to both thresholds in the system and change in physical and electrical characteristics due to heating.

REFERENCES: 26, p. 28; 32, p. 1599.

Physical Class	Physical Operator	Section 8
Chemistry Fluid Mechanics Optics and Light	Sensors — Distance Transformers — Information	Light Sensitivity

BINOCULAR COLOR RIVALRY

DESCRIPTION:

When two eyes are individually stimulated by different colors a binocular rivalry usually results. Two colors which are similar in wavelength and luminance will combine quite readily. However, if the two colors are from quite divergent regions of the spectrum, only transient mixtures, if any at all, will occur.

ILLUSTRATION:

Binocular rivalry occurs when different colored patches are placed on the two sides of a stereoscope; first one color is seen and then the other. Conscious effort has no effect since the shift occurs without warning. Such deterrent factors as differential brightness of the two colors, presence of figures, and movement all contribute to the difference in the amount of time each field is dominant. Under certain rather restricted conditions in some individuals there is a fusion of these two colors when they are presented to the eyes. However, when binocular fusion does exist, it coincides with, rather than contradicts, the laws of color mixture.

The explanation of this phenomenon may be found in the fatigue of the momentarily active response mechanism. Accordingly, alternation occurs as one mechanism is fatigued and the other increases in dominance.

MAGNITUDE:

The rate of alternation is a function of many factors. With low illumination each cycle lasts approximately 8.5 sec, whereas an increase in illumination will result in a cycle of approximately 2.5 sec. Similarly, the larger the field of vision, the more rapid the alternation.

Central vision results in more rapid alternation than peripheral vision. For example, the cycle duration increases with the distance of the stimulus from the fovea as follows:

	Seconds
In central vision	4.9
3.6° right or left	9.1
3.6° up or down	11.1
7.2° right or left	10.8
7.2° up or down	11.8

BINOCULAR COLOR RIVALRY, Continued:

SIMILAR EXAMPLES:

Depending on the particular colors involved or the manner of presentation, alternation or fusion of stimuli will occur. If a green filter is put in front of one eye and a red filter over the other eye, a sensation of "binocular yellow" occurs. This would appear to be an activity of the brain since only in the brain could the two excitations come together.

SAMPLE PHYSICAL ANALOGS:

Apparently this particular effect is due to involuntary shift of attention from one eye to the other and depends on the ability to perceive patterns. Since there are very few devices that analyze even monocular patterns, much less binocular patterns, there is no corresponding physical device which closely simulates this complex phenomenon. However, in a photometer, the intensity of light in a given wavelength is compared to a standard intensity by the use of a phototube. The difference of potential between the unknown and standard lights provides a quantitative measure of "color conflict".

REFERENCES: 37, p. 59; 149, pp. 399-400.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance	Light Sensitivity

BINOCULAR VISION

DESCRIPTION:

The principle of binocular vision can be explained by the theory of corresponding retinal points. When a human looks directly at an object, an image is formed by each eye and impulses are conveyed to both sides of the brain. Fusion of the two images occurs in the brain and only one image is seen. Stereoscopic depth perception is accomplished through triangulation resulting from binocular vision. It is present in man, higher primates, and in a number of predator animals.

ILLUSTRATION:

If an object is placed in a location where it can be seen by both eyes, it is considered as being common to the visual fields of both eyes. After the reflected light passes through the cornea, the lens, and the posterior chamber, it touches the wall of the retina at certain points. This occurs in both eyes at the same time. The image which is formed is the result of the light rays touching the same places, or points, on the retinas of both eyes simultaneously. These symmetrically located areas in both eyes are called the corresponding points. When this situation occurs, the resulting visual sensation in the brain is that of a single complete image. This complete condition is called binocular vision.

MAGNITUDE:

The visual field of each eye subtends an angle of about 160° in the horizontal median, and 145° in the vertical median. The visual field on each side is divided by a line passing vertically through the fixation point into two unequal parts, the outer or temporal area, the diameter of which is about 100° and the inner or nasal area, which is about 60° in diameter. At the outer or temporal limit of each eye is the crescentic area of monocular vision of about 35-40°. Therefore the horizontal diameter of the entire visual field is about 200°.

SIMILAR EXAMPLES:

Most animals have binocular vision by which certain parts of their environment are seen by both eyes at the same instant. However, in animals with lateral eyes, for example, the rabbit, vision is almost entirely monocular since the overlap of the two visual fields is very small.

SAMPLE PHYSICAL ANALOGS:

No precise analog of the complex process of binocular

BINOCULAR VISION, Continued:

vision exists, but some aspects of the process are modeled or simulated by correlation devices that have been used experimentally to plot contour lines on aerial photo stereo pairs. Similarly, a binocular range finder is an analog of binocular eyes. See also entry on "Binocular Color Rivalry" in this section.

REFERENCES: 7, p. 1412; 68, pp. 940-941; 144, p. 830.

Physical Class	Physical Operator	Section 8
Chemistry Fluid Mechanics Optics and Light	Sensors Internal Actuators Internal Transformers Information	Light Sensitivity

BUNSEN-ROSCOE LAW

DESCRIPTION:

The Bunsen-Roscoe law states that for the production of a given photochemical effect a constant quantity of energy is required which can be distributed within certain limits by varying either the level or duration of the illumination. This law helps to explain the hypothesis that vision by the retinal rods is fundamentally a photochemical reaction with visual purple as the photosensitive pigment.

ILLUSTRATION:

At any given brightness the eye adapts itself so that both the threshold and intensity of sensation are altered. The power of brightness discrimination in man is explained by the fact that in the sensory elements of the retina, which are adapted for a given intensity of light, photochemical processes are set up whenever the eye is exposed to a light of a just discriminable higher intensity. When the eye is fully adapted to absolute darkness its sensitivity is greatest, and its threshold the lowest, but the perception time is increased and the stimulus must act for a longer time. Two factors must therefore be considered when dealing with the sensitivity of the retina: (1) the energy incident on the retina, and (2) the time during which it acts.

As explained by the Bunsen-Roscoe law, to produce a given effect the product of the intensity of the light and the time during which it acts must be constant. Data on the human eye shows that for flashes of light of short duration the product of $I \times T$ is nearly a constant. As the duration of the flash increases, more and more energy is required to reach the threshold of stimulation, until eventually when the flash is of relatively long duration the threshold depends on intensity only, i.e., I = a constant. The area of retina exposed also modifies the threshold. When sufficiently small areas are illuminated, the transition from the relationship $I \times T = C$ to $I = C$ is more abrupt than with larger areas. This means that, for the eye, there is a certain critical length of time through which the stimulus must act in order to produce an effect.

MAGNITUDE:

In the dark-adapted eye the threshold is 7×10^{-7} mL. It has been calculated from very careful measurements that the chances are great that the energy absorbed by one rod upon stimulation is a single quantum. Since each quantum changes one molecule of visual purple, for us to see a just perceptible

BUNSEN-ROSCOE LAW, Continued:

flash of light there need be transformed photochemically only one molecule in each of 5 to 14 rod cells. If now the eye be adapted to a brightness of 2,000 mL, the threshold becomes 3.98 mL, its sensitivity drops to 1/16 in five seconds, and a rest of ten minutes in the dark is insufficient to restore its original sensitivity. As a further example of change in sensitivity, it may be mentioned that a dark-adapted eye can stand a glare of only 25 mL, while an eye adapted to bright sunlight can bear 16,000 mL.

SIMILAR EXAMPLES:

A law similar to the Bunsen-Roscoe law also applies to pressure sensitivity. The threshold for pressure sensation is related to the intensity of the stimulus and the area over which the stimulus operates. The adaptation time for pressure sensitivity is longer in the case of intense stimuli and briefer with large cutaneous areas.

SAMPLE PHYSICAL ANALOGS:

The Einstein photoelectric equation is analogous to the Bunsen-Roscoe law. Einstein stated in his equation that a given amount of energy, the binding potential, must be exceeded before the photoelectric effect can take place. The binding potential is simply the amount of energy required to free an electron from its orbit about an atom.

The Bunsen-Roscoe law applies to photochemical effects, regardless of the photochemicals involved. Photographic film is known to obey this law.

REFERENCES: 5, pp. 1249-1250.

CHROMATIC ABERRATION

DESCRIPTION:

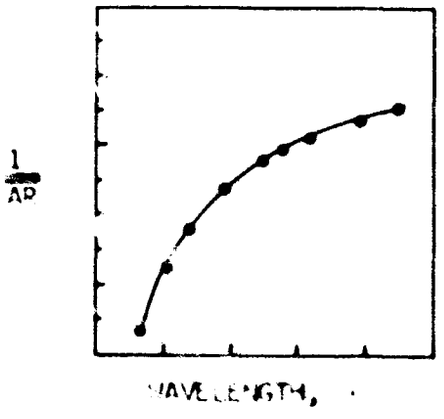
Chromatic aberration is that particular error in an optical system which results from the different refractibility of different wavelengths in the spectrum. It is manifested in the eye by a colored fringe on objects at focus on the retina.

ILLUSTRATION:

The human eye only partially corrects for chromatic aberration. For example, yellow light, being of medium wavelength, will be focused on the retina, whereas blue light, being of shorter wavelength, will be focused forward of the retina. Conversely, red light, being of longer wavelength, will be focused behind the retina. Other light is refracted according to its wavelength. Since the fovea is on the temporal side of the optical axis, blue light will fall upon the retina nearer to the axial point where it is cut by the optical axis. Thus blue light will appear to come from a point more distant than the point emitting red light. The image formed on the retina by blue light will also be smaller than that formed by red light.

MAGNITUDE:

The axial chromatic aberration of the eye can be measured by locating the conjugate focus of the retina for different wavelengths of light. The diagram below shows the average data for seven subjects tested by Wald and Griffin expressed in terms of an eye focused on a yellow (589 mμ) light point at infinity.



$\overline{AP}$ = DISTANCE FROM CORNEA TO THE CONJUGATE FOCUS OF THE RETINA

FIG. 13 EFFECTS OF CHROMATIC ABERRATION

SIMILAR EXAMPLES:

The colors surrounding the images on the retina are not ordinarily perceived. The terms chromatic stereoscopy and chromatic difference of magnification are used to describe the conditions of aberration which are similar to those described above.

SAMPLE PHYSICAL ANALOGS:

Chromatic aberration is a consequence of the uncorrected lens of the eye; thus, any uncorrected lens constitutes a physical analog of this effect.

REFERENCES: 7, p. 1394, 26, p. 38; 142, p. 321.

Physical Class	Physical Operator	Section 8
Chemistry Optics and Light	Transformers Information	Light Sensitivity

COLOR BLINDNESS

DESCRIPTION:

Color blindness is either a congenital or acquired defect which can be either total or partial in affecting an individual's ability to distinguish colors.

ILLUSTRATION:

There are two general types of color blindness:

a. Achromatism, or achromatopsia, is a condition of complete color blindness in which a person sees all the hues as shades of gray. A person with this condition is also called a rod monochromat; the only eye pigment that takes part in the vision of a rod monochromat is rhodopsin, found in the rods of the retina. Cones apparently do not play a part in the vision of a rod monochromat.

b. Dichromatism involves a person's inability to distinguish between colors.

1. Deuteranopia allows one to distinguish yellow from blue but not green from red, and when the condition is extreme, they see both red and green as shades of gray. Generally, deuteranopia is characterized by a spectrum of normal length. In the deuteranope, there is a lack of the retinal pigment chlorolabe (green sensitive) and a normal quantity of the pigment erythrolabe (red sensitive).

2. Protanopia also allows differentiation of blue from yellow but not red from green, although there is low sensitivity to red. Protanopia is marked by shortening of the spectrum at the red, and sometimes also at the violet end. The pigment chlorolabe is present in the protanope, but erythrolabe is absent.

MAGNITUDE:

By direct absorption measurements in the normal human foveal retina, two peaks have been found at 540 mμ and 590 mμ. A dichromat (person with dichromatism) shows only one or the other of the two peaks, depending on whether the condition is deuteranopia or protanopia. It has been postulated that the two peaks at 540 mμ and 590 mμ are produced by the green and red pigments, respectively.

Red-green color confusion is fairly common among men to the extent of approximately 7½% total or 5% deuteranope and 2½% protanope. About 1 woman in 1,000 is color-blind.

SAMPLE PHYSICAL ANALOGS:

A physical analog can be constructed for color blindness; for example, it is possible to make color film that will respond to, say, red and to yellow, but not be able to discriminate and

COLOR BLINDNESS, Continued:

distinguish all the possible colors, such as blues and purples.

Photosensitive devices, i.e. photoelectric cells, are efficient only when operated within certain portions of the light spectrum. This efficiency - wavelength relation, is analogous to the color sensitivity of the light sensitive pigments in the eye, and a photocell with limited response resolves color in a manner similar to the color-blind eye.

REFERENCES: 7, p. 1354; 26, p. 42; 116, p. 375; 124, pp. 291-304.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

CONTRAST

DESCRIPTION:

Contrast is the effect of intensification of the difference of sensation produced by the juxtaposition of two stimuli of the same modality, but differing markedly in quality or intensity.

ILLUSTRATION:

Contrast is best illustrated by the visual phenomena of color and brilliance and is either simultaneous or successive.

In simultaneous color contrast, the complementary color is perceived when a color is observed on a white, grey, or black background, as in the case of colored shadows. A color stimulus appears to change hue if it is contrasted with another color. The change in hue is always in the direction of the complement of the surrounding color. Therefore, a red stimulus surrounded by blue will assume a yellowish tinge. A red stimulus surrounded by green will appear redder. When black is placed against white, or vice versa, they set one another off; the black looks blacker and the white appears to be a purer white than if either were placed against a grey or colored background.

Contrast is also shown in other sensory areas, and with other types of stimuli. Perceptual figures, such as illusions, have also been known to demonstrate contrast.

MAGNITUDE:

The contrast effect is maximal when the brightnesses of the stimulus and its surrounding are equal. It is also directly related to the saturation of two colors when the brightnesses are equal.

SIMILAR EXAMPLES:

Two aspects of vision related to contrast are intensity discrimination and hue discrimination.

Chromatic dimming, another visual phenomenon related to this form of contrast, is a sudden decrease in the effect of a chromatic stimulus after the eye has been affected by its full intensity for a few seconds due to the influence of successive contrasts.

A physiological example of contrast is produced by the application of a medication which normally evokes one type of local skin reaction to a part of the skin which is reacting to another stimulus. For instance, calamine lotion containing phenol, a skin irritant in high concentration, is applied to an area of the skin with a poison ivy rash to neutralize the itching response produced by the poison ivy.

CONTRAST, Continued.

SAMPLE PHYSICAL ANALOGS:

Camouflage is indirectly related to contrast, since the object of camouflage is to reduce visibility which can be accomplished by the reduction of contrast.

REFERENCES: 7, p. 1341.

Physical Class	Physical Operator	Section 8
Chemistry Optics and Light	Sensors Distance Transformers Energy Information	Light Sensitivity

DARK ADAPTATION

DESCRIPTION:

When an individual passes from a well-lighted environment to darkness, at first nothing is seen, but after a few minutes there is a certain degree of vision, i.e., the outline of objects can be distinguished. In the course of dark adaptation the pupil dilates, the visual purple increases, and the chromatosomes are concentrated.

ILLUSTRATION:

If the threshold for light is measured at intervals after passing from bright light into darkness, it will fall sharply during the first 5 minutes then, after a short interval during which the curve tends to flatten, it again falls gradually, becoming stable after 20 to 30 minutes. The first drop is due to an increase in the sensitivity of the cones, the threshold of which remains stable at this level. The second gradual fall is due to an increase in the sensitivity of the rods. Nocturnal vision is due mainly to stimulation of the rods, and maximum sensitivity corresponds to the peripheral part of the retina, not to the fovea. A dark-adapted eye loses its adaptation if a bright light falls on the eye for only an instant.

MAGNITUDE:

The minimum amount of light that can be perceived by a fully dark-adapted retina is $1/10^{10}$ of the maximum stimulus in full daylight.

SAMPLE PHYSICAL ANALOGS:

The response of a photoconductor is dependent, to a large extent, on its light. In general, the response time is faster for a high ambient level of illumination than for a low level. However, the period of time for a photoconductor to change characteristics is quite brief and does not compare with the time required for adaptation.

REFERENCES: 7, p. 1642; 68, pp. 936-937.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

DIRECTION EYES

DESCRIPTION:

Direction eyes are the photoreceptive cells typically found in non-parasitic flatworms, or Turbellaria.

These photoreceptive cells are packed closely together behind shield-like cups of pigmented cells that are not penetrated by light. The angles at which these cups are placed on the two sides of the animal head are such that they permit the light, whenever it does not fall exactly parallel to the long axis of the body, to stimulate the photoreceptors on one side more than on the other side, so that the animal responds by turning until the stimulation received on both sides is equal.

ILLUSTRATION:

Planaria maculata, which possesses directional eyes, orients so that the two eyes are equally stimulated. This type of orientation involves the continuous comparison of intensities on two receptors simultaneously.

Establishing the relation between eye structure and possible modes of reaction, it has been demonstrated that a single flat eye can act as a direction receptor if the animal faces in various directions in turn and compares the intensities at successive points in time. With two suitably placed flat receptors a simultaneous comparison of intensities may be made, so that the animal is provided with the information necessary to turn in the direction of the higher intensity. In many animals, notably arthropods, vertebrates, cephalopods, and some planarians, the eye is composed of a number of separate elements, each of which can be stimulated from a particular direction. Consequently, by comparing the intensity of stimulation of the various elements, such an animal can be informed at any instant of the direction of the strongest or the weakest light.

MAGNITUDE:

The direction eyes of planaria consist of a highly pigmented retina of cup-shaped cells, inside of which are from two to thirty nerve cells.

SIMILAR EXAMPLES:

The mosaic eyes of insects are set immovably in the head, but the convex exposure of their surface is such that the marginal ommatidia may point outward at angles sufficient to include in the eye a wide range of vision.

SAMPLE PHYSICAL ANALOGS:

Photocells are analogs of direction eyes, themselves, but

DIRECTION EYES, Continued:

electronic circuitry using photocell inputs would be required to provide signals to move a pair of photocells to null their output difference. A complete control system of this type using photocell inputs has been used in some artificial satellites to provide a sun-seeking capability.

REFERENCES: 58, pp. 210-211; 116, p. 340; 144, p. 807.

Physical Class	Physical Operator	Section 6
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

EYEBALL OF VERTEBRATES

DESCRIPTION:

The eyeball of vertebrates is a complex structure formed by closely integrated parts, each one fulfilling a special function.

The ball is contained in the cavity of the orbit, where it is protected from injury and moved by the ocular muscles. Associated with it are certain accessory structures, viz., the muscles, fasciae, eyebrows, eyelids, conjunctiva, and lachrymal apparatus. The eyeball is embedded in the fat of the orbit, but is separated from it by a thin membranous sac, the fascia bulbi. It is composed of segments of two spheres of different sizes. The anterior segment is one of a small sphere; it is transparent and forms about 1/6th of the eyeball. It is more prominent than the posterior segment, which is a part of a larger sphere and is opaque; the posterior segment forms about 5/6th of the ball. The term anterior pole is applied to the central point of the anterior curvature of the ball, and that of posterior pole to the central point of its posterior curvature; a line joining the two poles forms the optic axis. The axes of the two balls are nearly parallel, and therefore do not correspond to the axes of the orbits, which are directed forward and to the side. The optic nerves follow the direction of the axes of the orbits, and are therefore not parallel; each enters its eyeball 3 mm to the nasal side and a little below the level of the posterior pole.

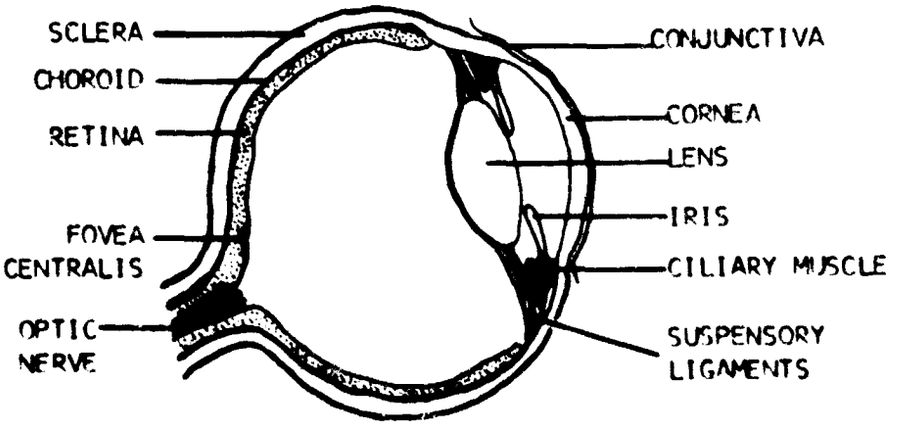


FIG. 14 VERTEBRATE EYEBALL

ILLUSTRATION:

Much of the eyeball is, as far as function goes, merely a blank space which needs only to be filled by some substance which

EYEBALL OF VERTEBRATES, Continued:

will not block or distort light rays passing through. This filling is in the form of liquids, generally referred to as humors. The principal cavity of the eyeball, between the lens and the retina, is filled by the vitreous humor, a thick, jelly-like material.

The most important functions of the eyeball are the diffraction and scattering of light. Light is diffracted by the pupillary margin and by the lens fibers and corneal epithelium; as a result of this and of spherical aberration, the retinal image is not made up of points of light but of diffusion circles, i.e., a bright central disc surrounded by light rings which diminish in intensity by almost imperceptible gradations towards the periphery. The relative size of the central bright area varies inversely with the diameter of the pupil and directly with the wavelength of the light.

None of the ocular media of the eyeball is perfectly homogeneous; owing to their colloidal nature a certain proportion of the light entering the eye is scattered, that is, it is not focused upon the retina but is deflected from the course which it would follow according to the laws of refraction if the contents of the globe were perfectly transparent. The colloidal particles have a size of the order of the wavelength of light. The quantity of scattered light is directly proportional to the square of the size of the particles, and inversely proportional to the fourth power of the wavelength (Rayleigh). Thus, the greatest scattering within the eyeball occurs with violet and ultraviolet light and the least with red.

MAGNITUDE:

The eyeball of the vertebrate is approximately spherical, being slightly flattened from above down. In the adult male human, it measures about 24 mm in its anteroposterior and transverse diameters and 23.5 mm in its vertical diameter. These measurements are less in the adult female, the anteroposterior being about 23 mm and the transverse diameters about 22.5 mm.

SIMILAR EXAMPLES:

See "Multifacet Eyes of Invertebrates".

SAMPLE PHYSICAL ANALOGS:

Functionally, the eyeball provides a means of focusing an image on the light sensitive retina. The retina, in turn, converts the pattern of light into a bundle of signals topologically related to the light pattern. The optical system of a television camera, although different in structure, provides a function similar to that performed by the lens and geometrical shape of the eyeball.

REFERENCES: 44, pp. 1095-1101; 68, p. 948.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

EYE LENS

DESCRIPTION:

The eye lens in man is a transparent cellular structure, both surfaces of which are convex, with the inner or posterior surface having greater convexity. It is compressible and elastic, especially in early life. The lens rests in a depression on the vitreous body, and is in contact on its anterior surface with the pupillary margin of the iris, thereby separating the anterior chamber from the smaller posterior chamber. It is enclosed in a thin capsule which is continuous with the suspensory ligament that anchors it to the ciliary ring. This ring, which is a thickening of the choroid layer toward the front face of the eyeball, is made up of a foundation of fibrous connective tissue, ciliary processes, ciliary muscles and blood vessels. The 60-70 ciliary processes are radiating ridges extending like cogs in a wheel toward the outer margin or the iris. This furnishes a point of attachment for the suspensory ligament that stretches from them to the capsule surrounding the lens, thereby holding it in position.

Although the convex curvature of the posterior surface is greater than that of the anterior surface, it does not vary appreciably. However, the anterior curvature is easily modified by the tension exerted on the lens through the ciliary muscles attached around the margin of the enveloping capsule. These ciliary muscles are smooth and involuntary, although their action is much more rapid than that of most other involuntary muscles.

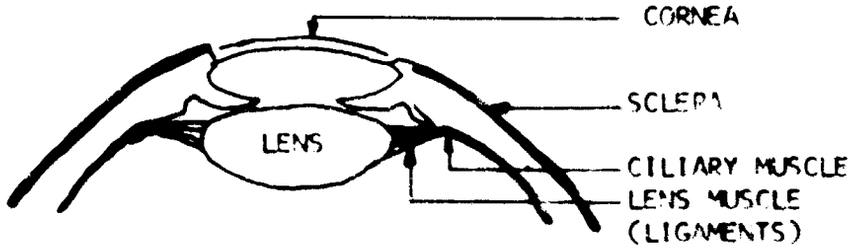


FIG. 15 LENS OF THE EYE

ILLUSTRATION:

The function of the lens is to refract (or bend) the light rays passing through it so that they will be brought to a focus on the retina, in the form of a sharply defined image, although

EYE LENS, Continued:

smaller and inverted compared to the scene outside of the eye.

When light rays pass through the pupil, the ciliary muscles either tighten or relax, thereby changing the shape of the lens. This causes the light rays, after passing through the lens, to be sharply focused on the retina.

MAGNITUDE:

When an object is brought closer and closer to the eye, a point is reached at which even the strongest contraction of the ciliary muscle will not result in a clear image of the object. This capability of the ciliary muscles to bring objects into full accommodation usually decreases with age, rapidly in the early 40's and more slowly after 50.

SIMILAR EXAMPLES:

The squid eye has a lens which provides images of light on the retina, although it is more nearly spherical than the lens in the human eye.

SAMPLE PHYSICAL ANALOGS:

The lens of a camera is a close analog (in functional terms) of the eye lens, although it is not flexible. Change of focus of camera lenses is accomplished by moving the lens relative to the film.

REFERENCES: 44, p. 1113; 68, p. 957.

Physical Class	Physical Operator	Section 8
Chemistry Optics and Light	Sensors Distance Transformers Information	Light Sensitivity

EYE PIGMENTS

DESCRIPTION:

Iris pigments. Eye pigments of various kinds are characteristic of the vascular layer, generally being much more abundant in the iris and giving distinctive color to the eye. The color of "blue eyes" is caused by dilute black pigment which is always located in the cells of the inner surface of the iris of all human eyes except those of albinos. Whenever any other eye color, such as brown, gray, or black, appears, it is due to the deposition of additional pigment, which is dominant over the blue color in the outer face of the iris.

Retinal pigments. The pigment rhodopsin, found in the rod cells of the eye, is responsible for twilight vision according to Rushton. The pigments chlorolabe (green-catching) and erythrolabe (red-catching) are found in the cones and are apparently responsible for the ability of the normal eye to distinguish different colors.

The retinal pigments are produced at a fairly constant, low rate. They are bleached by exposure to light, giving rise, in the bleaching process, to nerve impulses. These pigments are composed of opsin, a colorless protein, combined with retinene, a bent and twisted isomer of vitamin A. According to Hubbard, exposure to light straightens the retinene and triggers a number of chemical reactions; one or more of these reactions, in turn, triggers the nervous impulse to the brain.

MAGNITUDE:

The triggering of nerve impulses by light has been recorded a few thousandths of a second after a light is turned on. The time for complete regeneration of rhodopsin after bleaching was shown by Rushton to be about thirty minutes. For erythrolabe, regeneration after bleaching required about six minutes.

SIMILAR EXAMPLES:

A reflecting pigment present in the eyes of certain crustaceans consists of amorphous guanin. It forms a reflecting layer below the rhabdomes.

A hormone, isolated from the eyestalk of many crustaceans, has been shown to cause the following reactions:

1. Contraction of chromatophores in Crustacea.
2. Melanophore expansion in frog tadpoles.
3. Melanophore contraction in certain fishes.

See also section on "Nerve Sensitivity".

SAMPLE PHYSICAL ANALOGS:

Reversible color changes in certain dyes have been

EYE PIGMENTS, Continued:

observed following exposure to light in certain frequency ranges. Irreversible color changes can also be found in some dyes, such as those used in color film.

REFERENCES: 1, p. 245; 69, p. 34; 125, pp. 120-132; 144, p. 812.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance	Light Sensitivity

EYESPOTS

DESCRIPTION:

Definite organelles called eyespots are present in Euglena. These organs are associated with a localized photosensitivity. They are ball-like masses of opaque red or black pigment located near the inner end of the gullet.

ILLUSTRATION:

The eyespots function in association with the flagellum of the organism. In phototaxis the organism gradually alters its orientation through changes in direction of the beat of the flagellum in response to the periodic shading, until the organism becomes oriented.

In the Phytomonadida the stigma consists of a refractile structure which serves as a lens and covers the opening of a cup-shaped mass of pigments. The light-sensitive material is between the lens and the inner surface of the cup. The function of the pigment is to render the receptive organelle a directional detector useful in phototaxis.

MAGNITUDE:

Electron micrographic study reveals the eyespot area of Euglena to comprise forty to fifty tightly packed rods imbedded in a matrix.

SIMILAR EXAMPLES:

The eyespots of fresh-water Dinoflagellida are similar to those of Euglena. They are much larger and in general appearance they resemble the ocelli of flatworms and are called ocelli.

SAMPLE PHYSICAL ANALOGS:

Eyespots are relatively simple in function compared to the more complex light detection organs, such as the vertebrate eyeball. A photocell is analogous in functioning to the eyespot itself. See also comments on "Direction Eyes" in this section.

REFERENCES: 58, p. 340.

Physical Class	Physical Operator	Section 8
Acoustics Optics and Light	Sensors Distance Transformers Information	Light Sensitivity

FLICKER PHENOMENON

DESCRIPTION:

This phenomenon is produced by rapid, regularly intermittent stimulation in the visual or auditory field.

ILLUSTRATION:

The interruption of light by the rotation of a notched disc or by the reflection of light from a rotating disc divided into alternate black and white sectors results in the characteristic flickering or glittering sensation which is experienced when the periodic stimulation reaches a certain frequency. This sensation is caused by a light stimulus falling on the retina during the time of the positive afterimage of its predecessor. The suppression of the afterimage by the second stimulus causes the first sensation to end more abruptly, and, through contrast, to render the succeeding one more brilliant.

When the rotation speed is increased to the critical fusion frequency, the flicker disappears. Above the fusion frequency a light sensation results with a brilliance equal to the mean of the bright and dark impressions.

MAGNITUDE:

The maximum fusion frequency for man is 45 to 53 flickers/sec. This is lower than that for insects with "fast" eyes adapted for daylight vision. Some flies (Calliphora) have critical fusion frequency of 200 to 300/sec, and in bees it occurs at 255/sec. Porter's law states that the critical frequency for the abolition of flicker varies as the logarithm of the brightness of the stimulus, and independently of wavelength. High fusion frequency is related to a high sensitivity to shadows and to fine movements in patterns.

SIMILAR EXAMPLES:

Producing alternating periods of sound and silence, as in the flutter experiment, will result in a fluctuation of intensity received by the ear, which is an auditory effect analogous to the flicker phenomenon of vision.

SAMPLE PHYSICAL ANALOGS:

Almost any physical device which is band-limited constitutes an analog since the fusion effect is brought about by a limit on the resolution of the eye in terms of frequency of alternation of stimuli.

REFERENCES: 109, pp. 170-171; 116, pp. 377-378.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance Actuators External	Light Sensitivity

IRIS OF THE EYE

DESCRIPTION:

The iris is a pigmented disk-like membrane located in the most anterior part of the vascular tunic of the eye. It is perforated a little to the nasal side of the center by the pupil. The pupillary margin rests upon the anterior surface of the lens. The space between the lens and the cornea is divided by the iris into a larger anterior and smaller posterior chamber, the two chambers communicating through the pupil. The root of the iris is attached to the anterior surface of the ciliary body and is continuous through the pectinate ligament with posterior elastic lamina of the cornea.

The following five layers compose the structure of the iris: the anterior epithelium, the anterior limiting membrane, the stroma, the posterior membrane, and the posterior epithelium. The anterior epithelium consists of a single layer of flat endothelial-like cells. The stroma is composed of loose connective tissue. It transmits the vessels and nerves and holds numerous branched cells which, in dark eyes, contain pigment granules. The iris contains two involuntary muscles, the sphincter pupillae and the dilator pupillae. The sphincter pupillae is embedded in the stroma and comprises a band of circular fibers about 1 mm broad surrounding the pupil. When these fibers contract the pupil is constricted. The dilator pupillae constitutes the fourth layer of the iris. It consists of a thin layer of smooth muscle fibers which converge towards the pupillary margin where they blend with the fibers of the sphincter. At the root of the iris the dilator fibers pass into the ciliary body from which they take origin; when they contract they draw upon the pupillary margin and thus dilate the pupil. The posterior epithelium comprises two layers of deeply pigmented cubical cells; it is the continuation anteriorly of the pars ciliaris retinae.

The arteries of the iris which are loosely coiled form two vascular circles, one near the pupillary margin, the circulus arteriosus minor and the other near the root of the iris, the circulus arteriosus major. The two circles are connected by vessels which, arising from the larger circle, converge towards the pupillary margin where they form the smaller circle.

Blue or gray eyes owe their appearance to the pigment in the posterior epithelial layer as seen through the unpigmented stroma and other layers of the iris. The pigment cells of the stroma are responsible for the color of dark eyes, the shade varying with the quantity of pigment present.

IRIS OF THE EYE, Continued:

ILLUSTRATION:

The iris has three major functions:

a. It serves as an opaque screen to adjust the quantity of light reaching the retina under different intensities of illumination.

b. It prevents light from passing through the periphery of the lens thus reducing spherical and lateral chromatic aberration. The image is thus more clearly defined by restricting the transmission of light through the central part of the lens.

c. When the pupil constricts, the depth of focus of the eye is increased.

MAGNITUDE:

The visual system operates over a wide range of illumination (10^{12} times). Over this range the pupil area only alters by a factor of 16 times and, therefore, the pupil cannot maintain the retinal illumination at a constant level. The pupil light reflex does adjust the aperture of the eye so as to obtain the optimum visual activity at each level.

SIMILAR EXAMPLES:

The iris of the cat's eye adapts even more noticeably than man's iris when moving from a light to a dark environment.

SAMPLE PHYSICAL ANALOGS:

The diaphragm or f-stop of a camera limits the amount of light focused upon the film. The diaphragm is analogous to the iris of the eye in both function and purpose.

REFERENCES: 44, p. 1105; 68, pp. 955-957.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance	Light Sensitivity

MULTIFACET EYES OF INVERTEBRATES

DESCRIPTION:

Multifacet (mosaic) eyes are able to differentiate between the presence or absence of light and determine the direction of the source, and also receive light in such a way as to provide information for transmitting images to the brain. This type of eye is found in insects and crustaceans.

Mosaic eyes are most highly elaborated in insects. Although they are set immovably in the head, the convex exposure of their surfaces is such that the marginal ommatidia may point outward at angles large enough to include a wide range of vision for the whole eye.

In crustaceans, mosaic eyes are usually mounted on movable stalks that may be turned in various directions. The crayfish has two compound eyes, one on each side of the head, located at the ends of movable stalks which extend outward. Each eye is covered by a portion of the transparent cuticle called the cornea. The outer surface of the cornea is divided into many facets, or four-sided areas, which are the outer ends or openings of the ommatidia. The ommatidia are long visual rods separated from each other by dark pigment cells. The average number of ommatidia per single eye is about 2,500. Each ommatidium is composed of the corneal facet, corneagen cells which secrete the cornea, the crystalline cone, retinular cells, and rhabdom, with pigment cells surrounding each ommatidial unit. Fibers from the optic nerve, which enter at the base of each ommatidium, communicate with the inner ends of the retinular cells.

ILLUSTRATION:

Crayfish, like many other amphibians, are more active at night and at daybreak than during the remainder of the day. Their vision is more sensitive then because the pigmented cells are gathered at the base and top of each of the ommatidia, resulting in the more rapid detection of stimuli but with less discrimination as to its nature. The function of the crayfish eye is different in bright light than in dim light because of the migration of the pigment under the influence of light.

The apposition or exact mosaic image formed in the compound eye of the crayfish is also known as the Sedgewick Phenomenon of Image Formation, and occurs in bright light. The light rays entering ommatidia at an angle strike the dark pigment cells and are absorbed by them. Those rays which pass directly through the center of the cornea and along the central axis of ommatidia penetrate the retinulae to the optic nerve fibers. Therefore, the retinula of one ommatidium receives one resultant impression

MULTIFACET EYES OF INVERTEBRATES, Continued:

from light that reaches it. The adjacent ommatidia will receive a different stimulus. Thus, the stimuli from all ommatidia constitute an image similar to an inverted retinal image.

An erect, or superposition, image in the compound eye of the crayfish is formed by the incoming light rays being refracted by a large number of crystalline cones, and then being superimposed at the focus on the retina. In dim light the pigment migrates to both the outer and basal ends of the ommatidia. When this occurs the ommatidia do not act separately, but rather together, in order to throw a combined image on the retinular layer. The result is a much stronger stimulus although less distinct in detail as compared to the illumination intensity of the apposition image. This stronger stimulus is then transmitted to the retinulae.

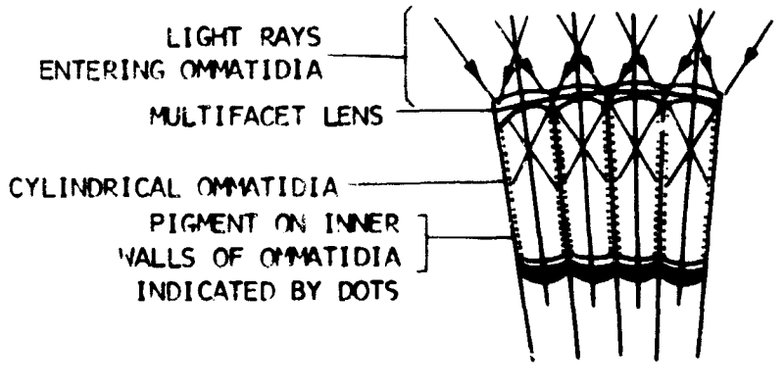


FIG. 16 LIGHT RAYS ENTERING THE COMPOUND EYE

MAGNITUDE:

The facet of the eyes of invertebrates is the external part of a long visual rod known as an ommatidium. As stated above, the average number of ommatidia in a single eye is 2500. Each ommatidium consists of one corneal facet, two corneagen cells, a crystalline cone formed by four cone cells, nine retinular cells, and a number of pigment cells.

SIMILAR EXAMPLES:

The grasshopper (Dissosteira carolina) has two compound eyes covered by a transparent cornea which is divided into a large number of hexagonal facets or openings to the columnar ommatidia. The grasshopper may be able to distinguish colors as do many other insects.

A parallel between the human eye and the crayfish eye is that both have high resolution with low sensitivity of vision as well as lower resolution with higher sensitivity of vision. In the human eye, higher resolution is provided in the fovea and high sensitivity is provided in the peripheral portions.

MULTIFACET EYES OF INVERTEBRATES, Continued:

SAMPLE PHYSICAL ANALOGS:

Fiber optic systems without lenses provide comparable image forming effects.

The different modes of operation of the apposition and superposition images are roughly comparable to a two-speed servo that is switched from narrow coverage fine resolution to wide coverage coarse resolution by the error signal level.

REFERENCES: 58, p. 419; 104, pp. 59-65; 144, p. 803.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Actuators External	Light Sensitivity

NICTITATING MEMBRANE IN BIRDS

DESCRIPTION:

The nictitating membrane in birds (and in many reptiles and mammals) is a thin transparent fold of deeply embedded skin acting as a third eyelid to the other eyelids. The highly elastic nictitans is stretched across a bird's eye by means of a long tendon which circles the eyeball to the rear and passes through a sling in the quadratus muscle, which holds the tendon away from the optic nerve. The inner surface of the membrane is covered with epithelial cells which have brush-like processes.

ILLUSTRATION:

The nictitating membrane in diving ducks, loons, and auks has in its center a clear lens-shaped window of high refractive index which improves vision under water. The brush-like process of the membrane brushes the cornea with tears at each flick. In addition the nictitans has a fold on its margin so slanted that it cleans the under surfaces of the eyelid on the reverse sweep. When the nictating membrane is shut over the eyeball, it prevents a flow of blurring tears during flight, which normally is incited by the stimulating contact of air against the cornea.

SIMILAR EXAMPLES:

The nictitating membrane of the frog's eye is somewhat similar to that of birds in function; however, it has a different derivation. In birds, the membrane arises from a vertical fold under the two eyelids, while in frogs, it is derived from the large lower eyelid, and is lubricated by the Harderian gland.

SAMPLE PHYSICAL ANALOGS:

Contact lenses provide a means for improving the refractive power of the eye similar to the central lens-shaped window of the nictitating membrane in diving birds.

The protective action of goggles or safety glasses is analogous to that of nictitating membranes in general.

REFERENCES: 144, pp. 824-828; 145, p. 81.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Distance	Light Sensitivity

NIGHT BLINDNESS

DESCRIPTION:

Nyctalopia or "night blindness" is a condition in which, under dim illumination, vision is poor. It may be so incapacitating that the victim is unable to move about in darkness. There are two different forms, one congenital and permanent, the other temporary and due to vitamin deficiency.

ILLUSTRATION:

Night blindness due to vitamin A deficiency is frequently found in undernourished populations. The vitamin bound to a protein forms the visual purple (rhodopsin) in the retina. Exposure to light converts rhodopsin into retinene or xanthopsin (visual yellow), which is an aldehyde of vitamin A bound to a protein. Light acting on visual purple stimulates the optic nerve endings and sends impulses along the nerves. In the dark, retinene is reconverted into visual purple. If there is vitamin A deficiency, the process of visual purple regeneration is retarded.

MAGNITUDE:

Measurement of spectral visibility on night-blind individuals reveals their eyes to have lost one-half their dual function; specifically, the remaining function is the typical high-intensity cone visibility curve.

SIMILAR EXAMPLES:

Taste "blindness", analogous to night blindness, is the term applied to action of the chemical compound phenyl thiocarbimide which varies in gustatory threshold over a wide range for different individuals, from a bitter taste to the complete absence of taste.

SAMPLE PHYSICAL ANALOGS:

By definition, a "blindness" in a sensor is an incapacity or inability to detect certain ranges or parameters of the sensed variable. Physical sensors are designed for a specific range of a variable, and they could be said to be "blind" to other ranges of the given variable and to other variables.

REFERENCES: 7, p. 905; 37, p. 34.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors Transformers Distance Information	Light Sensitivity

OPTICAL ILLUSIONS

DESCRIPTION:

Unreal or misleading images presented to the eye often cause errors in perception of patterns of lines called optical illusion, i.e., errors in apparent length, area, direction or curvature. In general they are errors in the perception of parts of a figure and are incidental to the perceived form of the whole figure, although a few (such as vertical-horizontal illusion) may be due to eye structure or the position of lines in the field of view. Illusions can be divided into contrast illusions and confluence or assimilation illusions.

ILLUSTRATION:

The brain can be deceived by perception of the eye of certain phenomena which affect visual judgment, as shown in the following illustrations.

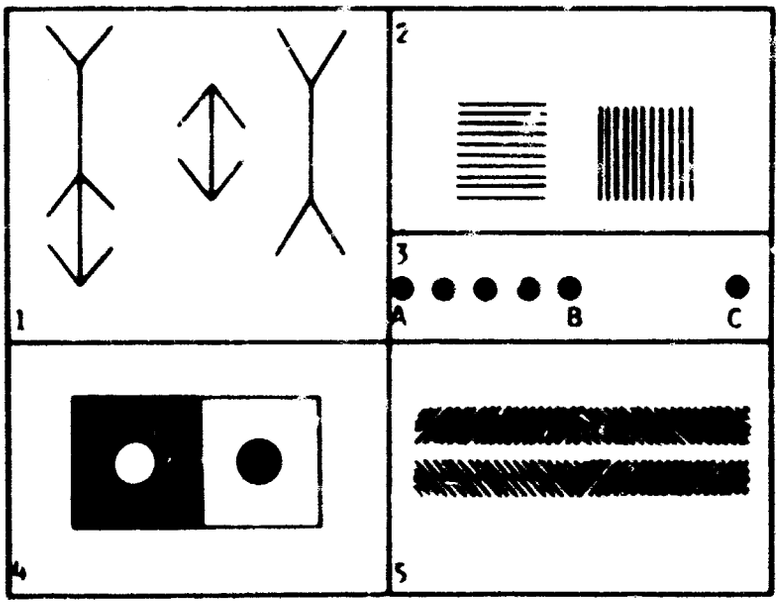


FIG. 17 OPTICAL ILLUSIONS. 1, THE DIFFERENT SEGMENTS OF THE VERTICAL LINES ARE ALL OF EQUAL LENGTH, ALTHOUGH SOME APPEAR TO BE SHORTER THAN OTHERS; 2, BOTH FIGURES ARE PERFECT SQUARES OF THE SAME SIZE, ALTHOUGH THEY APPEAR TO BE RECTANGLES; 3, THE DISTANCE FROM A TO B IS EQUAL TO THAT FROM B TO C; 4, THE WHITE AND BLACK DISKS HAVE THE SAME DIAMETER, BUT THE WHITE DISK APPEARS TO BE LARGER THAN THE BLACK ONE (IRRADIATION); 5, THE LONG HORIZONTAL LINES ARE STRAIGHT PARALLEL LINES.

OPTICAL ILLUSIONS, Continued:

Some of the better known optical illusions are:

a. Closure illusion: Single unconnected lines can give the impression of embossed block letters which have no breaks.

b. Hering illusion: Straight parallel lines appear to curve inward when they are drawn across a series of lines radiating from points beyond their extremities and intersecting above and below the lines.

c. Kundt's rule: A term applied to two different principles:

1. The principle that divided distances appear greater than objectively equal undivided distances (particularly the case of filled and empty spaces).

2. The principle that in attempting to bisect a line (horizontal) in monocular vision, there is a tendency to place the middle towards the nasal side.

d. Müller-Lyer illusion: The "arrow-head and feather" illusion, in which two equal lines appear unequal when acute angles are drawn at the ends of one and obtuse angles are drawn at the ends of the other.

e. Panum phenomenon: If two parallel lines near together are presented to one eye, and a single line parallel to them to the other eye, and then the single line is stereoscopically combined with either of the other two, the result is the experience of two lines in different planes, i.e., at different apparent distances, the apparently nearer being that of the combination.

f. Poggendorf's illusion: Produced by an oblique line passing at an acute angle, as if below two parallel lines. The two parts of the oblique line do not seem to be in the same straight line.

g. Proof reader's illusion: Evocation of the image of words by context, and by slight cues in the word as presented, with the consequent overlooking of typographical errors.

h. Staircase illusion: Reversible or ambiguous perspective in which a set of steps (stairs) can be seen as from above or from below, and the two views keep alternating. A perspective drawing of a cubic framework also illustrates this alternating or reversing effect.

i. Wundt's illusion: An illusion involving ring segments, where two annular lines are respectively crossed by short diagonal lines that appear to slant left and right.

MAGNITUDE:

Subjectively, equal distances may occasionally seem to be distorted by as much as 30%, although this would vary with the individual and with the illusion. It would be different with the same individual from time to time.

SIMILAR EXAMPLES:

Other types of distortion have been observed such as the blue-arc phenomenon, negative and positive afterimages, and Fechner's paradox, or the size-weight illusion wherein objects of

OPTICAL ILLUSIONS, Continued:

large size are perceived as lighter than smaller objects of the same weight. .

SAMPLE PHYSICAL ANALOGS:

A pattern-recognition machine often displays the tendency to ignore noise such as background spots in a pattern or small breaks in a line, and to interpret large and small alphabetical characters as similar. Hence, the machine would "see" a broken line as continuous (suggesting the closure illusion), a tilted character as though it were straight, and a large character as though it were small. A pattern-recognizing machine with certain of the various recognition characteristics of the human eye and visual cortex might even be expected to be subject to a large number of optical illusions similar to those of man.

REFERENCES: 16, pp. 463-464; 26, pp. 116, 149, 196, 276, 314.

Physical Class	Physical Operator	Section 8
Fluid Mechanics Optics and Light	Sensors Transformers Distance Energy	Light Sensitivity

PHOTONASTY

DESCRIPTION:

Photonasty is the response of bilaterally symmetrical organs, such as leaves and flower petals, to changes in light intensity. The direction of movement is largely determined by the anatomy or structure of the organ. Photonasty occurs more commonly in mature plant organs than in growing parts and hence in many cases it involves movements of variation or alternation rather than growth movements.

ILLUSTRATION:

Many flowers open under intense illumination and close in the dark or under weak illumination. The common dandelion opens on bright days but closes not only at night but on dull days or when artificially shaded. On the other hand, some flowers, like those of four o'clocks or tobacco, open in light of low intensity and close under intense illumination.

MAGNITUDE:

Artificially induced photonasty will not begin until some time after the stimulus is applied but may continue for several hours after the stimulus is removed.

SIMILAR EXAMPLES:

During the day, plants emit oxygen in the transpiration process. At night, the oxygen emission ceases and carbon dioxide is given off. Thus, the transpiration products are governed by illumination.

SAMPLE PHYSICAL ANALOGS:

Any system utilizing a change in light intensity as an activator is analogous to those biological systems exhibiting photonasty. Such systems include photoelectric control circuits for streetlights, garage door openers and lawn sprinklers and photographic film on which the image formed is due solely to the variation of light intensity exposing the film.

REFERENCES: 63, p. 243.

Physical Class	Physical Operator	Section 8
Chemistry Optics and Light	Sensors Distance Transformers Energy Information	Light Sensitivity

PHOTOPERIODISM

DESCRIPTION:

Photoperiodism is the response of plants to length of the daily period of illumination. In temperate regions, plants are subjected to alternations of light and darkness, with lengths ranging from 15 hours in summer to about 9 hours in winter. The growth of plants and particularly the development of flowers and fruits is influenced by the length of day.

ILLUSTRATION:

Normally, plants can attain the flowering state only when the length of day falls within specific limits which are reached during certain seasons of the year. Some plants, such as radishes and lettuce, bloom only during periods of illumination of 12 hours or more. Such plants are called long-day plants and bloom in midsummer. Others, called short-day plants, require less than 12 hours for flowering and bloom either late in autumn or early in the spring. Examples of short-day plants are most of the spring flowers and such autumn-flowering plants as ragweeds, asters, cosmos, and scarlet sage. Other plants, such as the tomato, respond to all periods of illumination and therefore can bloom all year.

MAGNITUDE:

Long-day herbaceous perennials, such as some of the sedums, have been kept for 8 to 9 years under short-day illumination without flowering, while controls receiving normal day lengths of illumination flowered every year during this time. After having been kept under a short day for 8 years, one plant was given a full day length of summer and bloomed normally at the same time as did the control plants.

SAMPLE PHYSICAL ANALOGS:

Artificial biological clocks have been constructed that are triggered by specific periods of illumination in much the same fashion as photoperiodic plants.

REFERENCES: 63, pp. 231-234.

Physical Class	Physical Operator		Section 8
Chemistry Optics and Light	Sensors Distance	Transformers Energy Information	Light Sensitivity

PHOTOSENSITIVE PROPERTIES OF RHODOPSIN

DESCRIPTION:

Rhodopsin (visual purple) is the main photosensitive substance in the retinal layer of the mammalian eye. Most photoreceptor cells consist of a carotenoid compound and a protein, retinene and opsin, respectively, which combine to form the most common form of rhodopsin. The composition of rhodopsin varies in accordance with the amount of light present. It is found predominantly in the rods, the more light-sensitive of the receptors of the eye.

ILLUSTRATION:

Rhodopsin can be made to decompose and regenerate in the test tube. This involves three gradual changes from a red-purple substance to transient orange and finally to visual yellow, at which point the application of materials from the blood and body tissues will result in regeneration of the original compound. The amount of decomposition is directly proportional to the amount of light absorbed.

MAGNITUDE:

Rhodopsin responds to light wavelengths which range from 400 to 600 mμ with its greatest efficiency being around 500 mμ. Rhodopsin has a molecular weight of 40,000 and contains one retinene per molecule.

One of several isomers of rhodopsin, referred to as porphyropsin (visual violet), has its maximal absorption power at 522 mμ.

SIMILAR EXAMPLES:

Several animals have compounds with properties of rhodopsin and porphyropsin. The frog tadpole which is just entering metamorphosis is known to have both of these substances with porphyropsin being more dominant; further on in its evolution, the two substances equalize until finally the emergent frog has rhodopsin as the dominant substance.

SAMPLE PHYSICAL ANALOGS:

The sulfides and selenides of cadmium, selenium, zinc and lead are photosensitive. These chemical compounds are used as the photosensitive elements in photoelectric cells and are therefore analogous to rhodopsin.

The silver halides are also photosensitive and are used extensively in the emulsion of photographic film.

PHOTOSENSITIVE PROPERTIES OF RHODOPSIN, Continued:

REFERENCES: 77, pp. 147-149; 83, pp. 356-359.

Physical Class	Physical Operator	Section 8
Optics and Light	Sensors: Distance Actuators: External	Light Sensitivity

PHOTOTROPISM IN INSECTS

DESCRIPTION:

Phototropism in insects refers to the reaction of an insect to light, and the influence of the light on the animal's position. This may be a positive or negative reaction.

ILLUSTRATION:

Light of short wavelengths, such as blue and violet, is usually more attractive to insects than other colors. Black infuriates bees, but white seems to have no effect upon them. It is said that enraged bees will congregate upon and sting the black spots on Holstein cattle, but will not attack the white spots.

Insects generally orient themselves with their heads directly toward or directly away from the light source. The moth is not attracted by light but is oriented by it and, in constantly adjusting its head to the light, is drawn into it.

MAGNITUDE:

Insects as a class respond to electromagnetic radiations from approximately 2537 Å to approximately 7000 Å, that is, from the ultraviolet to the infrared. At the long end of the spectrum, the maximum effective wavelength for most insects is of the order of 6500 Å. The firefly Photinus pyralis is one of the few insects known to be stimulated by longer wavelengths as judged by its response to flashes of approximately 5600 Å to 6900 Å.

SIMILAR EXAMPLES:

Plants also respond to light, often by growing toward the source of light.

SAMPLE PHYSICAL ANALOGS:

See comments under Physical Analogs in the entry "Direction Eyes" in this section.

REFERENCES: 36, pp. 216-217; 119, p. 988.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

SENSITIVITY TO LIGHT AND TO PATTERNS OF LIGHT

DESCRIPTION:

Many protozoa plus some metazoan larval forms, show a definite response to light stimulation. When they turn toward the light they are positively phototropic, and when they turn away and try to avoid it they are negatively phototropic. Some unspecialized cells in various phyla can detect infrared and visual radiation, and many lower forms of animal life contain certain specialized photoreceptive cells in the skin which enable them to distinguish light from darkness. Proceeding up the scale of evolution, the most highly developed light sensitivity apparatus in the animal kingdom is found in the eyes of birds and men.

Although the glands and muscles of the eyeball are better developed in mammals both in structure and efficiency, birds, particularly birds of prey, have the best eyes among vertebrate animals. The accomodation apparatus in the bird's eye is especially rapid and effective.

ILLUSTRATION:

Earthworms have specialized photoreceptive cells which enable them to distinguish light from dark. If earthworms are above ground at night, they will react to the increased light intensity at dawn and burrow back into the earth. In most instances this negative phototropism is used by the animal as a defense mechanism.

Some animals have photoreceptive integumentary cells located outside the eyes; some lizards, including chameleons, respond to light by changing their skin color. This is illustrated when a lizard, temporarily blinded, responds to a ray of light focused on its skin in a dark room.

According to Slonaker, there are many color-receiving cones in the bird's retina which spread out over a large area as far as the equator of the eyeball. The bird's retina contains more than one foveal depression for accentuated visibility, and the iris contains striated muscle fibers.

Two examples of the excellence of bird vision are chickens and hawks. Chickens can be pecking at the ground with eyes focused closely to it, and become instantly aware of a high-flying hawk appearing only as a speck high overhead. Hawks can detect, from a great height, a mouse moving along the ground.

An important feature of the human eye is the jitter of the eyeball, without which the human eye cannot see static images in a normal manner. When images are stabilized on the retina, the perceived patterns fade and reappear, but are not seen in their

entirety except for brief periods of time (Prichard). It has been suggested by Platt that the jitter enables us to see straight lines.

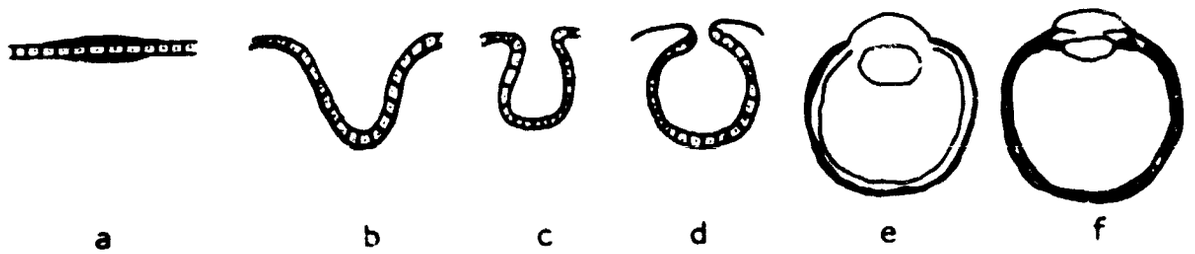


FIG. 18 EVOLUTION OF THE EYE

The eyespots of the medusa (Fig. a), are more highly evolved than the light sensitive skin areas of other forms of life, because in the medusa, the sensory cells are clustered more densely together. Many sea snails and other marine animals have visual cells that are recessed (Fig. b) and (Fig. c), providing improved directional sensitivity. The "pit eye" of the Nautilus (Fig. d), closes almost completely except for a small hole, and in the next evolutionary step, does close completely, forming a lens (Fig. e). It is likely that the faceted eye of the insect also evolved from the eyespot, bulging out rather than in, with addition of more photosensitive cells, to provide its directional sensitivity to light. The primitive faceted insect eye would not be as protected as the eye in Fig. a, for example, but would provide a wider field of view.

MAGNITUDE:

At its most sensitive, the eye can detect light when only a very few quanta are absorbed by the retina and, at the other extreme, it can still detect differences in intensity when the light is more than 10,000,000 times stronger than the minimum required to reach its absolute threshold.

The threshold for light can be raised or lowered to a considerable degree; e.g., a dark-adapted eye is sensitive to approximately 0.0000007 mL using achromatic light, while the eye adapted to a luminosity of 2,000 mL is not sensitive to light intensities below 4 mL.

SIMILAR EXAMPLES:

Infrared sensitivity, such as found in the snake, is related to light sensitivity.

SENSITIVITY TO LIGHT AND TO PATTERNS OF LIGHT, Continued:

SAMPLE PHYSICAL ANALOGS:

Physical devices sensitive to light have been constructed using various effects such as photochemical, photovoltaic, and photoresistive. Mosaics of light sensitive devices have been used in the construction devices that respond to or process patterns of light. Several such devices are referenced below.

REFERENCES: 57, p. 107; 86; 116, pp. 337-338; 144.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance Transformers Information	Light Sensitivity

THE VERTEBRATE RETINA

DESCRIPTION:

The retina, which is the inner sensory layer of the eyeball, is a double invaginated gastrula-like cup that is essentially a part of the brain. It is composed of an outer part, a thin layer of pigmented cells, and an inner, thicker part containing the sensory receptors, or rods and cones, plus accessory cellular elements. Response of the rods and cones to light is due to the action of the light-sensitive pigments. See the entry "Photosensitive Properties of Rhodopsin" for details of the action of visual pigments.

The region of clearest vision in the retina is a small area in the direct line of the optical axis behind the lens and opposite the pupil. It has a distinctly yellowish color and is called the macula lutea. In its center is a conical depression, the fovea centralis, which is the specific region of sharpest vision. The region is covered with more color-receiving cones than rods. Within the fovea centralis the product of the image area and the light intensity is constant for threshold stimuli. This is a constant power relationship and is termed Charpentier's law.

On the inner surface of the eyeball is a blind spot at the point where the large optic nerve leaves the posterior part of the eye. Rays of light which strike this area are not seen because of the absence of photoreceptive rods and cones.

The principal cells of the eye include:

a. Cone cells which are photoreceptors sensitive to color, and rod cells, which are sensitive to all wavelengths of light, provide the discrimination of patterns of light. These cells are packed close together along their longitudinal axis and vertically in relation to the depth of the retina. Each cell registers light from a small area.

b. The rods and cones form synapses with a layer or stratum of bipolar relaying intermediate cells, which in turn connect with large ganglionic cells. The elongated axons of the latter cells group together to form the optic nerve that extends outside the eyeball to the brain. Each ganglionic cell may connect with several intermediate cells, and each of these in turn may receive stimuli from several rods and cones.

c. The amacrine cells are cross-connecting neurons in the layer of the intermediate cells; they join the triple systems together laterally. There are also non-nervous supporting cells which extend from one face of the retinal layer to the other, thereby acting in somewhat of a skeletal capacity.

THE VERTEBRATE RETINA, Continued:

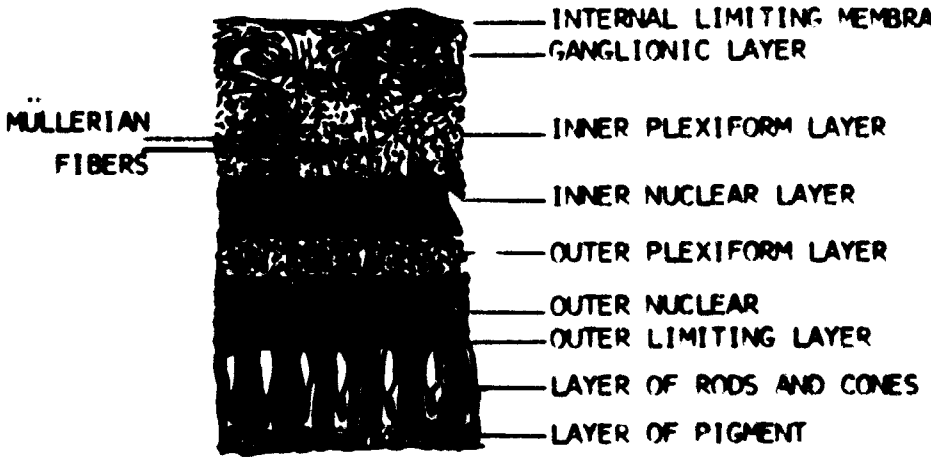


FIG. 19 CROSS SECTION OF THE VERTEBRATE RETINAL LAYER

ILLUSTRATION:

Willy Kuhne performed an experiment in which an albino rabbit was allowed to look at the sky through a barred window for 3 minutes after the rabbit was dark-adapted to allow rhodopsin accumulation in its rods. After the 3-minute exposure, the rabbit was killed and its retina was removed and fixed in alum. This resulted in a picture of the window with a clean pattern of its bars printed upon the retina in bleached and unaltered rhodopsin. Kuhne called the process optography and its products optograms.

MAGNITUDE:

There are approximately 7 million cones and 125 million rods in the human retina. The human fovea has approximately 12,000 cones and no rods. The cones are sensitive to a minimum light intensity of about 10^{-2}mL, the rods being sensitive to a much lower intensity, about 10^{-6}mL. The number of nerve fibers in the human optic nerve is generally in the range 800,000, so there is evidently considerable data reduction in the retina.

SIMILAR EXAMPLES:

See also the entry on "Sensitivity to Light and to Patterns of Light".

SAMPLE PHYSICAL ANALOGS:

Certain types of photocell circuits obey a law similar to Charpentier's law. The retina may also be compared to a photographic film.

REFERENCES: 26, p. 246; 116, pp. 347-350; 144, pp. 810-811.

Physical Class	Physical Operator	Section 8
Mechanics Optics and Light	Sensors Distance	Light Sensitivity

VISION IN BEETLES

DESCRIPTION:

When animals look at moving objects, numerous physiological interactions between their adjacent visual units occur. In studies on the beetle, Chlorophanus viridis, Hassenstein and Reichardt have shown this to be a process of cross-correlation. The visual units of movement perception in this case are the numerous facets, or ommatidia, in the beetle's eye. Since the anatomical angle between two adjacent ommatidia is only 6°, a very small light stimulus would be received by only one of these facets and not by those adjacent to it. Beetles, as do many animals, react to movement perception in the visual field by optomotor reactions. This means that they follow the movement which they perceive by actively turning the head or body to reduce the movement stimulus being received by their eyes. This could be considered in terms of a feed-back loop. The physiological reactions of these test beetles enabled Hassenstein and Reichardt to determine that the strength of insects' optomotor reactions depends on two main factors: the velocity of the moving pattern and the efficiency of the stimulus of the individual light changes which comprise the stimulus situation itself.

An extensive analysis of all the experimental data obtained during these investigations indicated that the beetle was able to derive velocity information from a shaded background that was in motion.

ILLUSTRATION:

During the neurological investigations of the eyes of beetles, the direction and strength of the optomotor response have been used as indicators of the perception processes being performed by the nerves. In these experiments the feedback loop of the reaction mentioned above was terminated by positioning the beetle so its optomotor reactions could be observed and noted. This did not influence the animal's position in relation to its visual environment.

Hassenstein and Reichardt placed the beetle, Chlorophanus viridis, inside a hollow cylinder on the inside of which were perpendicular black and white stripes. As the cylinder rotated, the beetle tried to follow the movement, and the response by the beetle to this observed movement reduced the relative speed of the surroundings to a residual speed they called the "slip". Consequently, the insect, together with its surroundings, formed the feedback loop. While the cylinder was being turned, very small, point-like light stimuli were directed in succession to the beetle's eye. The real physiological interaction was found to occur between the aftereffect of one stimulus and the effect

VISION IN BEETLES, Continued:

of the next one. The first of two successive stimuli is modified by a filter which acts like a low-pass.

MAGNITUDE:

The results showed that (1) the simplest successive repetition of light changes that is able to prompt an optomotor response consists of two stimuli in adjacent ommatidia; (2) while these optomotor responses are being produced, each ommatidium (optical unit) can function only in conjunction with its immediate neighbor, or the next one. There does not seem to be any physiological interaction between ommatidia which are separated by more than one unstimulated ommatidium.

The maximum reaction was elicited with a time interval between two stimuli of approximately 150 milliseconds. The strength of the reaction was found to decrease with both longer and shorter time intervals. The maximum time interval that was shown to release a reaction was slightly more than 10 seconds, after which it disappeared. The strength of these optomotor reactions of the beetle was found to be a quadratic function of the stimulus intensities. It was also concluded that the direction and intensity of these optomotor responses of the beetle reflect the multiplication result of signs and intensities of the individual stimuli. There seems to be a physiological mechanism linking the sensory input and the motor output by a process which works according to the multiplication formula.

A mathematical model was made using two linear low-pass filters, of time constant τ_E, and two similar filters of time constant, τ_D. The latter filters represent the inertia of conduction lines which cross between the two straight channels. The following formula for calculating the output of the system, was derived by Reichardt:

$$f(v) = \text{const} \left(\exp\left[- \frac{x}{v\tau_E} \right] - \exp\left[- \frac{x}{v\tau_D} \right] \right)$$

in which τ_E and τ_D = the time constants of the output filters.

v = the velocity of the stripe pattern relative to the sensory inputs.

x = the spatial distance between the two inputs.

When the two time-constants were assigned specific values, such as τ_E = 3500 milliseconds, and τ_D = 46 milliseconds, for the calculation of the theoretical curve, the latter was found to match the actual experimental results.

SIMILAR EXAMPLES:

It is possible that the conclusions of Hassenstein and

VISION IN BEETLES, Continued:

Reichardt, based on their research on the beetle's eye, might apply to the optomotor responses of numerous other animals having multifaceted eyes, as, for example, the crayfish and mosquito.

SAMPLE PHYSICAL ANALOGS:

This work has already led to the proposal for a ground-speed indicator to be used in airplanes. This instrument would be based on the function of only two of the hundreds of facets in this beetle's compound eye.

REFERENCES: 54, pp. 617-619; 55; 117, pp. 303-317; 128, pp. 41-47.

Physical Class	Physical Operator	Section 8
Electricity and Magnetism Optics and Light	Sensors Distance Transformers Information	Light Sensitivity

VISION IN FROGS

DESCRIPTION AND ILLUSTRATION:

Although man and the frog can both regulate the amount of light that enters through the pupil, the frog's eye is unable to accommodate for viewing both near and distant objects. This is due to the inability of the lens to change its form or be brought closer or further away from the retina. Frog's eyes do not move to follow a moving object.

The basis of the excitation factor in the frog's vision is the pattern of local variation of intensity and not the light intensity itself. The frog does not seem to be interested in stationary objects in front of him. However, he will jump toward any moving object in front of him. Lettvin, et al, in their investigations found that there are four types of nerve fibers evenly distributed throughout the retinal surface. This results in four distinct, parallel-distributed "channels" or paths through which the frog's eye tells the brain about the visual image it sees in terms of the local pattern. It appeared to be relatively insensitive to illumination level.

Of the four types of retinal nerve fibers the sustained contrast detectors have axons which are unmyelinated (i.e., not enclosed in a protective myelin sheath) and will not respond when the general illumination is disrupted. For example, when the sharp edge of an object, which is either lighter or darker than the background, moves into this detector's field and stops, it will react immediately, and continue regardless of the edge's shape or size compared to the receptive field. The sustained discharge can be interrupted or greatly reduced in these axons when all the light is off. After the light is turned on again, there is a very slight pause followed by a resumption of the sustained discharge. This resumption is due to the fact that a contrast in some of the fibers in this group is "remembered" or retained. Some of these axons maintain a small amount of activity that is present only if contrast were there before.

The net convexity detectors also have unmyelinated axons and respond under various conditions. According to Lettvin and his co-workers, this group of axons contains the most remarkable elements in the optic nerve. This type of fiber does not respond to a general illumination change, but will respond to a small object that subtends an angle of 3 minutes of arc within the field of vision.

The fiber will not respond to the straight edge of a dark object moving through its receptive field, nor to one which is brought there and stopped.

Moving-edge detectors have myelinated fibers which conduct nerve impulses at speeds of approximately 2 meters per

second. These fibers react to any edge that can be distinguished while it moves through the receptive field, which is 12° wide. The light-to-dark ratio of the edge to the background does not seem to affect the action of these particular fibers. This is demonstrated by the absence of a reaction when a stationary object is placed in front of the frog's eyes. However, if the object is moved across this field of vision, the response is much more rapid. This total response to nearby object movement is faster and more definitive than responses to total illumination changes, although it does vary only slightly with the general illumination.

In the net dimming detectors, the impulse transmission speed, according to Lettvin, of these myelinated nerve fibers has been measured at 10 meters per second; these net dimming detectors have a large receptive field of about 15°. The effect produced by a moving object has been shown to be directly related to its size and relative darkness compared to its surroundings. When a dark object is moved through the field, after the background light has been dimmed, the resulting effect is the creation of a second dimming pulse. Immediately after the object passes through the field, the overall brightness increases.

In addition to the four main types of detectors just described, there is another but smaller group of afferent fibers; however, this group unlike the other four, does not seem to have specifically defined receptive fields. Their mutual function, although individually performed, is to measure the absolute degree of darkness over a wide area with a long time constant. In other words, as it becomes darker, these nerve fibers are discharged more frequently.

In general, the functional activity of these four "channel-producing" nerve fibers may be summarized as follows:

(1) The frog's contrast detector nerve fiber receives stimuli which tell the frog if there is a sharp boundary present, either moving or stationary.

(2) The convexity detector, in a larger area, indicates when

(a) the object has a curved boundary,

(b) it is darker than the background and moving on it, or

(c) these detectors remember the object when it has stopped, as long as the boundary is sharp and completely within the visual area of the frog.

These detectors are also most active if the enclosed object moves in relation to the background and lose their "memory" of the object if a shadow comes between the eyes and the object.

(3) The moving edge detector tells if there is a moving boundary in an even larger area in the field.

(4) The dimming detector determines how much dimming occurs in the largest area, influenced by the distance from the

VISION IN FROGS, Continued:

center and by the speed with which it happens.

MAGNITUDE:

The actual functions of the four main detectors are independent of the general illumination. There are 30 times as many contrast detectors and convexity detectors as there are moving edge detectors and dimming detectors. The sensitivity to edge sharpness, or increments of motion in the first two, is higher than in the last two.

SIMILAR EXAMPLES:

The cells of the lateral geniculate of cats have a response similar to the retinal ganglion cells of those of the frog. Most of them respond when the retina is stimulated by diffuse light.

Goldfish ganglion cells give on, off, and on-off discharges as do those of the frog. Each cell serves as a receptive field of which the center gives an on response and the periphery an off response.

SAMPLE PHYSICAL ANALOGS:

E. E. Loebner has described a device for simulating the frog's eye. More generally, other pattern recognition devices are discussed under Physical Analogs in the entry on "Sensitivity to Light and to Patterns of Light" in this section.

REFERENCES: 88. pp. 1940-1959.

Section 9:

LOCOMOTION

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BIOLOGICAL ASPECTS OF LOCOMOTION

Locomotion is achieved in a variety of ways by living creatures, and, in general, is accomplished by a complex, coordinated set of actions. Even in the amoeba, which moves by pseudopods developed by an internal streaming or flowing of protoplasm, the problems of initiation, control, and cessation of streaming require significant coordination.

Over thousands of years the environment of an animal may affect the development of specialized organs of locomotion. Organs adapt to take advantage of the properties of the medium through which the animal moves or the surface over which it travels. For example, the weight of the bodies of marine animals is supported almost entirely by the water, and the organs of locomotion provide motion but not any load-bearing action. Air, however, provides very little support for birds Adaptations by birds to the less dense medium of air include hollow bones (which provide greater strength to weight ratio), increased surface area of the propelling organ (which provides greater lift), and increased metabolism (which permits an increased power output).

In animals with a well-developed central nervous system locomotion is initiated by the brain and is carried out by the contraction of muscles caused by the action of nerve impulses on muscles. Since the muscles are connected to various skeletal structures in the vertebrates, the muscular contraction produces position changes.

The speed of locomotion in animals is dependent upon the extent to which specialized organs for locomotion have developed. In land animals, such as the horse, deer, and cheetah, speed in running is achieved by four jointed limbs of about equal length, with a well-developed musculature In the dolphin, it is believed that a part of its speed is achieved by the prevention of turbulent flow using muscles attached to the skin

PHYSICAL ANALOGS IN GENERAL

Locomotion is the ability of a system to transport itself from one location to another and includes the diverse possibilities of travel through gaseous, liquid, or solid media along the interface between less dense and more dense media

From a physical point of view, locomotion in the animal kingdom is not very efficient because of the almost inevitable use of third class levers In the third class lever, the lifting force is applied between the fulcrum and the load. However, the jointed limb, which is an extended series of third class levers, has the property that the point of application of force can be varied or adjusted with respect to the point of attachment of the

limb. In brief, a jointed limb is useful for irregular terrain. This property has led to the suggestion that jointed limbs might be more suitable for lunar or planetary exploration vehicles than wheels or treads. The control of jointed limbs is far more complex than the control of a wheel, however, and although mechanical structures of this type could easily be built, the control problem for jointed limbs has received very little study thus far

The capability for flight in animals is of two general types: flapping wing and soaring. Gliders provide a direct analog to soaring animals, but flapping-wing aircraft have been notoriously unsuccessful. For powered flight, the propeller and the jet have proved far more efficient than flapping-wing devices -- so much so that very little serious attention has been or is likely to be directed toward the design of such devices.

Physical Class	Physical Operator	Section 9
Fluid Mechanics Materials Properties Mechanics	Transformers Energy Actuators External	Locomotion

AMOEBOID MOVEMENT

DESCRIPTION:

Many microorganisms move by a type of locomotion which does not require muscle tissue. This type of movement is exemplified by the amoebae which move from place to place by means of finger-like protrusions of the body, known as pseudopodia.

ILLUSTRATION:

A pseudopodium is produced where the elastic strength of the plasmagel is weakest. A hyaline cap is formed and the plasmagel is forced into it by the contraction of the plasmagel solates at the posterior end so that new plasmasol flows forward becoming a gel again just back of the tip of the pseudopodium. Thus amoebae move forward in the direction of the pseudopodium as a result of the solation and gelation of the endoplasm.

MAGNITUDE:

The rate of locomotion of amoebae depends in part on the temperature; it increases to a maximum at 24°C, then decreases to 28°C increases again to 30°C and decreases above this point, becoming zero at 33°C. The maximum speed attained by amoebae is, at most, a few centimeters per hour.

SIMILAR EXAMPLES:

The white blood cells, which can move around independently and have the capability to penetrate capillary walls, both behave and look much like the amoeba.

SAMPLE PHYSICAL ANALOGS:

No analog of amoeboid motion is employed for the production of motion in physical devices. However, the use of materials in alternately liquid and solid form is quite common in the molding and casting of materials.

REFERENCES: 128, pp. 76-77.

Physical Class	Physical Operator	Section 9
Mechanics	Transformers Energy Actuators External	Locomotion

ANNELID LOCOMOTION

DESCRIPTION:

Locomotion by annelids is achieved by contraction and expansion of the radial and longitudinal muscles. These actions are aided by a series of siliceous bristles whose orientation and degree of extension are under muscular control.

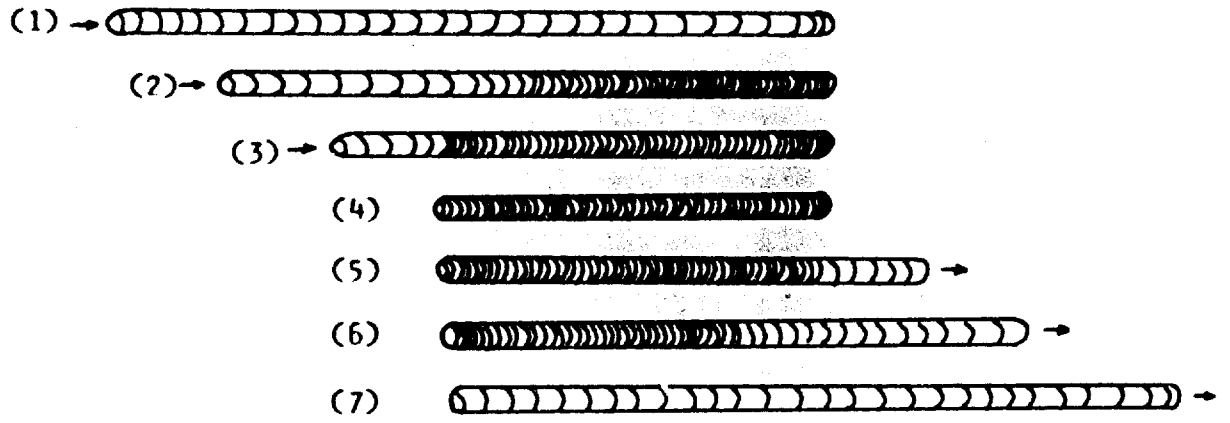

FIG. 20 LOCOMOTION OF EARTHWORM BY CONTRACTION AND EXPANSION OF RADIAL AND LONGITUDINAL MUSCLES

ILLUSTRATION:

There are two sets of muscles located in the cylindrical wall of the earthworm's body. One of these sets extends longitudinally from the anterior to the posterior end, coinciding with the longitudinal axis. The second set of muscles runs circularly around the body and perpendicular to the first set. This circular arrangement also extends the full length of the body.

When the circular muscles contract, the longitudinal ones relax. This exerts a pressure on the fluid contents in the main body cavity (the coelum). The body fluid then transfers this pressure to the longitudinal muscles which are at rest, causing these muscles to stretch toward the anterior end. This results in a lengthing of the earthworm's body in a forward direction. Upon contraction of the longitudinal muscles, the worm's back end is drawn forward, thereby shortening the body again by muscular contraction. The small bristle-like setae on the ventral surface of each segment are drawn forward by this muscular action. Then they take hold of, or "stick into" the ground, preventing the body from moving backward.

ANNELID LOCOMOTION, Continued:

MAGNITUDE:

The muscles of the earthworm are composed of flat, ribbon-like individual fibers, which are shown by electron microscope measurement to be 20 μ wide, 2.5 μ thick, and 2 to 3 mm long. According to Prosser and Hanson, each individual fiber has peripheral fibrils which move in a right-hand spiral diagonally at a 10° angle to the main fiber axis when the fiber is extended. When the fiber is shortened by contraction as much as 50%, this fibril angle increases to 30%. Each of the spiralling fibrils is comprised of about 100 filaments and shows a periodicity of 300 to 500 Å.

SIMILAR EXAMPLES:

The locomotion of the snake is similar in that the snake's scales provide a unilateral coefficient of friction (i.e., one in which resistance to motion is greater in one direction than the opposite). The scales of fish also constitute a surface of unilateral coefficient of friction with respect to water and very likely contribute to the forward motion of a fish.

SAMPLE PHYSICAL ANALOGS:

Although no precise physical analog of annelid locomotion is employed for physical devices, it is conceivable that the two principles employed in this motion, expansion-contraction and the ratchet, could be used for self-propelled vehicles for use over irregular and unknown terrain as would be the case in, say, lunar exploration. The problems of controlling this type of motion are much simpler than the problems of controlling jointed limbs.

REFERENCES: 51, pp. 111-122; 116, pp. 423, 426.

Physical Class	Physical Operator	Section 9
Mechanics	Actuators External	Locomotion

ESCAPE MECHANISMS OF SHRIMP

DESCRIPTION:

The mechanism employed by shrimp for backward leaps (or "escape leaps") is a combination of (1) abdominal segments which are hinged on a "rocker" principle at points above and below which the cross-sectional area is equal and (2) the infolding of intersegmental membranes. This arrangement permits flexion and extension without any energy loss from changes in internal volume. Further, although powerful muscles and a large tail fan are required for "backward" speed, the inertia of the cephalothorax must exceed that of the abdomen for the mechanism to be effective. The entire response is coordinated through the giant fibers of the central nervous system.

ILLUSTRATION AND MAGNITUDE:

Usually a single stimulus elicits only one backward leap, achieved by one flip or a few successive flips of the tail. However, some shrimps, e.g., Homarus, Panulirus and Galathea, often speed backward at 0.9 to 8.0 m/sec by flexing the abdomen repeatedly and steering with their tails. In Malacostraca the abdomen is flexed ventrally, with many of the appendages pointing forward for "streamlining". There are reports of certain shrimp which are able to propel themselves 15 m or more through the air (into the wind) in "escape leaps".

SIMILAR EXAMPLES:

The escape mechanisms of shrimp can be compared to some types of swimming in other animals. The use of appendages as oars occurs in certain insects, turtles, and numerous other vertebrates to give added speed in escaping from danger.

SAMPLE PHYSICAL ANALOGS:

While no direct physical analog of the shrimp leaping mechanism is presently found in devices, the constant-volume flexion and extension in the shrimp has an analog in the constant-volume joints of a space suit. Since the shrimp exoskeleton is fairly rigid, it is conceivable that the principles of the shrimp constant-volume joints could be adapted to provide a more rigid space suit.

REFERENCES: 61, pp. 1-252; 92, pp. 157-248; 95, pp. 353-354; 97, pp. 791-800; 150, p. 57.

Physical Class	Physical Operator	Section 9
Aerodynamics Fluid Mechanics Heat and Thermodynamics Mechanics	Sensors Contact Internal Transformers Energy Actuators External Internal	Locomotion

FACTORS AFFECTING WINGBEAT FREQUENCY IN INSECTS

DESCRIPTION:

The factors which affect wingbeat frequency in insects are species, age, sex, environmental influences (such as air temperature, density, and composition), and internal factors such as fatigue.

ILLUSTRATION:

At any given age, the wingbeat frequency of female Drosophila is less than that of males. The effects of temperature change on the flight of different insects are confusing in their variety. With certain species, alterations in rate of wingbeat are produced by variation in air temperature, whereas in other cases the response has been found nearly independent of this factor.

Immediately after emergence from the larval stage, the frequency of wingbeat in the Drosophila is relatively low. It rises during the first few days of adult life to a plateau which is maintained until the onset of senescence.

In continuous flight of Drosophila, the average wingbeat frequency follows a typical pattern. Once flight has begun, the rate fluctuates for some time. After some minutes of flight a decline sets in and continues until the rate has dropped to a value equal to about half or two-thirds of the original figure. Flight then ceases.

MAGNITUDE:

Wingbeat frequency is approximately inversely proportional to the cube root of the moment of inertia of the wings. The frequency is also inversely proportional to atmospheric pressure. The maximum wingbeat frequency that has been recorded is 2218 beats/sec in a male midge, Forcipomyia.

Large-winged, light-bodied species of insects, such as the papilionid and pierid butterflies, have rates of wingbeat of about 4 to 20/sec; the static-load is of the order of 0.01 g/sq cm per wing surface. Heavy-bodied, small-winged insects, such as flies and bees, vibrate the wings 100 or more times per second under normal conditions; here the wing loading is of the order of 0.05 to 0.35 g/sq cm.

SIMILAR EXAMPLES:

The same factors affecting wingbeat frequency in insects will also affect limb movement and locomotion in animals. In Daphnias exposed successively to different intensities in a light field without a gradient, the speed of locomotion increases as a function of the logarithm of the intensity.

FACTORS AFFECTING WINGBEAT FREQUENCY IN INSECTS, Continued:

SAMPLE PHYSICAL ANALOGS:

Age of the physical components, temperature and humidity will, to a small degree, affect the output frequency of both audio-frequency and radio-frequency oscillators. These factors are analogous to the factors affecting the wingbeat frequency in insects.

REFERENCES: 116, pp. 445-447; 119, pp. 591-604.

Physical Class	Physical Operator	Section 9
Fluid Mechanics Mechanics	Transformers Actuators Energy External	Locomotion

FISH LOCOMOTION

DESCRIPTION:

Swimming movements of the fish's body are produced by four longitudinal bands of muscles, one heavy band on either side along the back and a thinner band on either side of both trunk and tail. These muscles are arranged in zigzag myotomes. Most fish have a spindle-shaped and laterally-compressed body, as the perch, this form offering very slight resistance to progress through water.

ILLUSTRATION:

The principal locomotor organ of fish is the tail. By alternating contractions of the muscular bands on the sides of the trunk and tail, the tail with its caudal fin is lashed from side to side, moving in a curve shaped like a figure "8". During the flexions and extensions of the tail, the trunk is curved to bring about an extension or forward stroke and a weak flexion or non-effective stroke. The paired lateral fins (pectoral and ventral) are used as oars in swimming when the fish is moving slowly. They also aid the caudal fin in steering the animal, for, although the course is altered largely by the pointing of the head and tail in the desired direction, the lateral fins assist in swerving the body to one side or the other, either by executing more powerful strokes on one side, or by the expansion of one fin and the folding back of the other. Movement of the fish up or down results from holding the lateral fins in certain positions so that the fins act as elevators or planes for the ascent or descent.

It is likely that the scales of fish are functional in providing additional action in terms of boundary layer fluid flow and skin friction in effecting locomotion.

MAGNITUDE:

The frequency of the undulating movement in steady forward motion in the dogfish is 54/min. One of the highest frequencies appears in the mackerel at 170 waves/min. The corresponding velocities of the waves are 55 and 77 cm/sec for these fish.

The magnitude of this forward movement depends upon the angle made by the surface of the fish and the axis of its forward movement, and the velocity of the transverse movement of the fish's body.

FISH LOCOMOTION, Continued:

SIMILAR EXAMPLES:

The motion of the flagella, or cilia, in single-celled organisms, which is similar to the motion of the stingray tail, is another example of propulsion through water. Other forms of propulsion through water are those employed by amphibia, human swimmers, insect back swimmers using paddling or rowing motions, and the squid jet propulsion.

The ratchet effects described in "Annelid Locomotion" and "Snake Locomotion" can be compared to the unidirectional boundary layer flow over the fish's scales.

SAMPLE PHYSICAL ANALOGS:

Considering the scales of the fish, it is apparent that an undulation which would cause water to flow both forward and backward along different parts of the sides of a stationary fish would produce a net forward thrust on the fish since the skin friction of the forward flowing water is greater than that of the backward flowing water. Under these circumstances a fish would start moving forward because of the ratchet effect of the scales, even though there were no other propulsive mechanism. Rapidly vibrating surfaces of any aquatic vehicle based upon this type of boundary layer mechanism utilizing artificial scales, could conceivably result in motion of the vehicle through water, and possibly through other media, such as mud and quicksand.

The rubber flippers worn by frogmen on their feet produce a moving surface inclined at an angle to its line of motion similar to the fish's tail.

REFERENCES: 57, pp. 443-444; 118, pp. 478-483; 153, pp.131-141; 158, pp. 1, 27.

Physical Class	Physical Operator	Section 9
Aerodynamics Fluid Mechanics	Transformers Energy Actuators External	Locomotion

FLIGHT OF THE HUMMINGBIRD

DESCRIPTION:

Hummingbirds are unique among the birds in their ability to fly backward and sideways as well as forward. They are also able to remain in stationary flight for an indefinite period of time.

ILLUSTRATION:

The flight of the hummingbird is directly related to its unusual wing movement. Other birds exert power only during an upward wing beat, but the hummingbird exerts power during a downward wing beat as well.

When moving forward or backward, the hummingbird's wing plane is tilted correspondingly forward or backward. Hovering is accomplished by moving the wings back and forth in a horizontal motion, keeping the axis of movement in the same plane.

MAGNITUDE:

The range of the hummingbird's wing beat extends from the male Callipalex ametheptina's rate of 80 beats/sec to that of the Patagona gigas which is about 10 beats/sec.

SIMILAR EXAMPLES:

The flight behavior of many insects is similar to that of the hummingbird. For example, the wasp flies backward by reversing the normal plane of wing rotation, likewise deriving power from a downbeat as well as an upbeat of the wings.

SAMPLE PHYSICAL ANALOGS:

Although there are no aircraft that fly by means of oscillating (flapping) wings, stationary flight is obtained by the rotating wing (blades) of a helicopter. Other experimental vertical-lift craft direct a jet downward to accomplish the same end.

REFERENCES: 19, pp. 604-605, 620-621; 46, pp. 100-115.

Physical Class	Physical Operator	Section 9
Aerodynamics Electricity and Magnetism Fluid Mechanics	Transformers Energy	Locomotion

INSECT FLIGHT MUSCLES

DESCRIPTION:

The muscles of insects directly concerned in flight are the tergum and the pleura, with their associated endoskeletal extensions. Sternal derivatives play only a small part. They contribute to internal bracing and are seats for muscle attachment. The muscles which effect the movements of the wings are classified into five groups on the basis of function and position. They are:

Muscle Group	Location	Principal Function in Flight
1	dorsal	depression
2	basalar	depression, protraction, pronation
3	subalar	depression, supination, retraction
4	dorsoventral	elevation
5	axillary	flexion (retraction), plication, minor adjustments of the wing path

ILLUSTRATION:

Depression of the wings occurs in most insects as the result of contraction of the dorsal muscles, which are stretched mainly between the anterior and posterior tergal phragmata. As these muscles shorten, the tub-shaped notum bulges outward and upward at the lateral margins, which are connected to the first and third axillary sclerites of the wing via the anterior and posterior notal wing processes. The wing is thus pivoted downward over the fulcrum provided by the head of the pleural wing process. At the same time, the relative movement of the articulations is such as to introduce components of protraction and pronation into the movement of the wings.

The basalar muscles have a tendinous connection with the anterior axillary region of the wing so that a pull on the basalar muscle tends to tilt the costa of the wing forward and downward.

The subalar muscles are associated with ventral extensions of the second axillary sclerite, a downward pull which depresses the ventral area of the wing and thus contribute also a component of supination. This action occurs toward the close of the downstroke.

Elevation of the wings is accomplished through contraction of the dorsoventral muscles. When the wings are fully depressed,

INSECT FLIGHT MUSCLES, Continued:

these muscles, whose dorsal attachments are on the more lateral areas of the tergum, are extended and in the most advantageous position for exerting their full force.

The axillary muscles are concerned in modifications of the pattern of wing movement. They act principally in flexion, plication, and, in conjunction with the subalar group, supination of the wing. By shifting the relative positions of the articulating elements, they alter considerably the path followed by the wing under the driving force supplied by the contraction of the main depressor and elevator groups.

MAGNITUDE:

The minimum time required for a complete cycle of contraction and relaxation of a muscle receiving a single nerve impulse is about 15 to 20 ms. Some insects' movements are so fast, 50-70 cps, that they could not possibly be produced by what is described as tetanic contractions. The wing beat in some insects is much faster than the rate of 50-70 cps, so the flight muscles receive nerve impulses at a frequency much lower than the rate of wing beat. As an example, there may be only one nerve impulse for each three or four wing movements.

SIMILAR EXAMPLES:

Hummingbirds and kestrels beat their wings so rapidly that they can hover in the air without moving in any direction. The wing beat frequency of some hummingbirds is from 60 to 70/sec, similar to that of insects.

SAMPLE PHYSICAL ANALOGS:

Since the wing beat frequency is higher than the nerve impulse frequency (input frequency), it may be regarded as a stepped up frequency such as provided by a frequency doubler, or it may be considered as a special type of frequency converter which requires only one input frequency. (A general type of electronic frequency converter requires the excitation of a square law detector by two different frequencies.)

REFERENCES: 19, pp. 584-587; 129, p. 72; 151, p. 806.

Physical Class	Physical Operator	Section 9
Fluid Mechanics Mechanics	Actuators External	Locomotion

JET PROPULSION OF THE SQUID

DESCRIPTION:

The squid ejects a stream of water which propels it backward when the animal is attempting to capture its prey or to escape capture itself. This "jet propulsion" is brought about by the rapid and repeated contraction of a strong muscular outer wall of the large mantle cavity, which forces the large quantity of water contained therein out through the short muscular neck-like tube.

ILLUSTRATION:

When the squid is in search of food or when it is being attacked, it contracts the muscles around the mantle wall forcing the water from the cavity and propelling the squid in the opposite direction. The muscular siphon through which the water is ejected can be bent either backward or forward allowing the squid to swim in almost any direction by a slight change in muscular tension around the siphon.

MAGNITUDE:

The Humboldt Current squid can attain speed up to 20 mph. When jet-propelling through the water at this speed the lobes of the caudal fin are closely wrapped around the body and the arms are held tightly together, forming an acute bundle in front, so that the animal, in this condition, is tapered at both ends, and passes through the water with the least possible resistance.

SIMILAR EXAMPLES:

The method of jet propulsion is similar in many respects in most of the cephalopods, although there are some differences in the mechanism. Octopuses have no internal funnel valve and some, such as the Cirromorpha, have only a very narrow opening. However, they do swim by jet propulsion, not as fast as squids, maintaining speeds up to 8 mph.

SAMPLE PHYSICAL ANALOGS:

Although underwater jets for the propulsion of boats are a relative novelty, forms of jet propulsion are commonly used for aircraft.

REFERENCES: 157, pp. 138-139.

Physical Class	Physical Operator	Section 9
Aerodynamics Fluid Mechanics Mechanics	Sensors Contact Distance Transformers Energy Actuators Internal	Locomotion

MECHANICS OF INSECT FLIGHT

DESCRIPTION:

Insects that fly have either one or two pairs of wings. Although insect wings are usually flexible, they are flat and have no appreciable curvature on the upper surface as do most subsonic airfoils. The essential scheme of insect wing motion is that of a figure eight. The figure eight traced in flight is elongated, somewhat bent, and inclined forward at the bottom.

ILLUSTRATION:

The work of lifting and propelling is done on the downward and forward stroke, while the upward and backward stroke effects the recovery of the wing for the next cycle. The wing twists about its long axis as the result of its own variable flexibility from leading edge to trailing edge and the articulation of the levers and muscles that move it. Thus the wing is made to push against the air during the working portion of its travel and to minimize resistance during recovery. With this compound motion, the wing draws air from above and ahead and pushes it below and behind. In doing so it imparts an equal and opposite upward and forward push to the insect.

MAGNITUDE:

Some insects can fly up to 300 miles without stopping. Even smaller insects travel long distances. Aphids regularly cross the North Sea between England and the European continent, a distance of several hundred miles; in Africa black flies may start an epidemic of cattle disease 200 miles from their nearest breeding site, having traveled 100 million times their body length without stopping.

SIMILAR EXAMPLES:

The stingray fish uses a wing-like structure to propel itself in the water.

SAMPLE PHYSICAL ANALOGS:

See comments under Sample Physical Analogs in "Flight of the Hummingbird".

REFERENCES: 11, pp. 117-142; 65, pp. 92-98; 68, pp. 85-92; 119, pp. 578-588.

Physical Class	Physical Operator	Section 9
Fluid Mechanics Mechanics	Transformers Actuators Energy Internal	Locomotion

METACHRONAL RHYTHM

DESCRIPTION:

Metachronal rhythm is the orderly succession of initiation of beats of cilia located in a spatial sequence on ciliated surfaces. Each cilium along one axis is slightly out of phase with the ones in front of and behind it, in the direction of the wave propagation. At right angles to this wave, cilia beat isochronically, or in phase with one another, giving an optical picture of waves passing over the epithelium. Very little is known about the mechanisms of the coordination and control of cilia. It is probably more complex among protozoans in which a number of complex locomotor patterns may be exhibited by a single individual.

ILLUSTRATION:

This rhythm occurs as the result of a pattern of beating cilia, as in ciliated epithelial tissue, or multiple limbs, as in Polychaeta. If the effective stroke is considered as moving backwards, then each cilium or limb is at a slightly earlier stage in the beat cycle than the one behind it, and slightly later than the one in front of it.

Among ciliated tissues from various sources, the direction of the wave bears various relationships to the direction of the effective stroke. In the frog's mouth, for instance, the metachronic wave and ciliary effective strokes are in the same direction.

Cilia reached by a metachronal impulse strike out from their momentary position in a plane perpendicular to the cell surface and directed towards their point of articulation. As the wave of activity passes away, the cilia becomes limp, bends out of the plane of beat to the right. It then swings, stiffening again from base to tip, counter-clockwise and parallel to the body surface until reached again by the next impulse.

Metachronal rhythm also occurs in microscopic single-celled animals such as the paramecium in which it forms the latter's means of locomotion.

MAGNITUDE:

A typical cilium uses a paddle stroke effect. It vibrates backwards and forwards in regular intervals, completing a cycle in about 1/15 second.

SIMILAR EXAMPLES:

The neuromotor system in control of locomotion in Euplates is similar.

Also, see "Flame Cell as a Pump", p343, and "Peristalsis"

METACHRONAL RHYTHM, Continued:

p. 324.

SAMPLE PHYSICAL ANALOGS:

A boating crew in a racing shell moves the oars in a synchronized rhythm to propel the boat in a manner similar to the cilia of the paramecium's body.

The distributor action in controlling the phase of pistons in an automobile is analogous.

REFERENCES: 45, p. 232; 116, p. 482.

Physical Class	Physical Operator	Section 9
Electricity and Magnetism Mechanics	Sensors Contact Actuators External	Locomotion

THE MUSCLE RECEPTOR ORGAN OF CRUSTACEA

DESCRIPTION:

The muscle receptor organ is present in most stomatopods as well as all Natantia and Anomura. In stomatopods the muscle receptor organs are a pair of modified muscle fibers, occurring on both sides of the dorsal musculature in each of the six abdominal segments and in the extensor muscles of the seventh and eighth thoracic segments. Near the middle of each muscle receptor fiber the muscle tissue is replaced by a region of connective tissue into which dendrites of the associated sensory neurons penetrate.

ILLUSTRATION:

The functional study of muscle receptor organs demonstrates that flexion of the crayfish tail evokes action potentials in two nerve fibers of each muscle receptor organ. One fiber adapts slowly and continues to discharge during constant stretch for an hour. The other fiber adapts to zero within one minute during constant stretch. Stimulation of the motor nerves causes contractions of the receptor muscles and also gives rise to action potentials in the sensory neurons at a frequency which is dependent upon the amount of stretch applied to their dendritic terminals. Stretch is applied to the latter either by flexion of the abdominal musculature or by contraction of the receptor muscle due to the stimulation of the motor fibers. The interaction of these two factors governs the discharge frequency of the sensory neurons, causing the response to a standard motor stimulus to vary with the initial tension applied to the receptor.

MAGNITUDE:

The larger muscle in stomatopods, the "fast receptor", has a contraction lasting 60-100 ms. The smaller "slow receptor" muscle has a longer lasting contraction.

SIMILAR EXAMPLES:

The intrinsic ganglion system of the crustacean neurogenic heart is a similar example. Considered as a small, complex "central nervous system" with intrinsic automatism, it has an output in the form of spikes in the motor axons to the heart muscle cells, and an input in the form of impluses reaching it.

SAMPLE PHYSICAL ANALOGS:

The governor on a motor which senses immediate changes in speed and opens or closes a valve or relay is analogous to the muscle receptor organ.

THE MUSCLE RECEPTOR ORGAN OF CRUSTACEA, Continued:

A Foucault pendulum is analogous in that its support is free to rotate with the rotation of the earth. The point of maximum excursion of the bob will traverse a circle in 24 hours.

REFERENCES: 20, pp. 69-73.

Physical Class	Physical Operator	Section 9
Fluid Mechanics Mechanics	Actuators External	Locomotion

SNAKE LOCOMOTION

DESCRIPTION:

Snake locomotion is accomplished by four different undulations or waving motions, namely the concertina, the sidewinding, rectilinear and horizontal. The most widely used is the lateral or horizontal undulation of the body. The ribs serve as movable appendages and the body grips the ground with the broad backward-projecting scales of the ventral surface.

ILLUSTRATION:

Snakes move on land or in water by the movement of spinal column and muscles, which push the sinuous body horizontally against the resistant surrounding medium. Most snakes can glide through a twisted glass tube, but not through a straight one of about their own diameter. A few thick-bodied snakes (e. g., boas, pythons, vipers) can progress slowly in a straight line essentially by means of contraction waves which pass along the costocutaneous musculature from head to tail. These specialized muscles are attached to the ventral scales which engage projections in the ground and draw the animal along. The North American sidewinders (Crotalus) and the Egyptian sand vipers (Cerastes) move over loose sand by means of a series of horizontal double loops which engage the earth and propel the animal sideways. Some snakes, such as the Asiatic chrysopelea, can ascend vertical walls and tree-trunks. This is done by the laterally-keeled ventral scales engaging any tiny projections on the surface.

MAGNITUDE:

Snakes give an illusion of moving faster than they actually do because of their rapid sideways whippings and undulating. The whip snakes can move up to 12 mph, although most other snakes move no faster than 7 mph.

SIMILAR EXAMPLES:

Locomotion of the earthworm is similar to that of snakes. The earthworm moves by the expansion and contraction of its longitudinal and radial muscles, causing an undulating or wave-like movement of the body.

SAMPLE PHYSICAL ANALOGS:

The motion of a rope loop going as a wave toward the end is similar to annelid movement. If the rope is dropped from the hand, the entire rope will move slightly in the direction of the wave on the ground.

SNAKE LOCOMOTION, Continued:

REFERENCES: 113, pp. 520-521.

Physical Class	Physical Operator	Section 2
Fluid Mechanics	Transformers Actuators Energy External	Locomotion

TUBE FEET OF STARFISH

DESCRIPTION:

Tube feet, or podia, are found in Echinodermata as hollow extensile appendages connected to the vascular system, and are hydraulic mechanisms. In starfish they end in suckers and are locomotor in function.

ILLUSTRATION:

When the tube foot is to be stretched out, the ampulla contraction arises as a result of muscular activity running circularly around the ampulla. The tube foot is thus distended and its broad flattened end is brought into contact with the surface of the object upon which it is moving. The muscles of the tube foot, which are arranged in a longitudinal fashion, then commence to act. The pressure of the water prevents the tearing away of the sucker from the object to which it adheres, and the starfish is slowly drawn forward as the fluid in the tube foot flows back into the ampulla.

MAGNITUDE:

The tube feet of starfish can develop a suction pressure as high as 3,000 grams per orifice area, and by a periodic pulling or suction process can open a bivalve mollusk.

SIMILAR EXAMPLES:

In brittle stars and crinoids, the suckers are absent, but the tube feet are still important organs, exhibiting locomotion by lateral arm flexion and extension similar to the squid.

SAMPLE PHYSICAL ANALOGS:

An aspirator bulb is used to produce a partial vacuum in a manner somewhat similar to that of tube feet.

REFERENCES: 1, p. 337; 58, pp. 517-518; 81, pp. 114-122; 116, p. 393.

Physical Class	Physical Operator		Section 9
Materials Properties Mechanics	Sensors Contact Internal	Transformers Energy Actuators External	Locomotion

WALKING MOVEMENTS OF INSECTS

DESCRIPTION:

Walking and running by insects depend, basically, upon stepping movements of the individual legs and coordination of the stepping cycle of each leg with similar but out-of-phase cycles in the other legs.

ILLUSTRATION:

Tarsal flexion (grasping) enables the insect to obtain a foothold during the propulsive movement of the leg. Flexion of the tarsal claw brings an adhesive pad or pulvillus in contact with a smooth surface or provides a hook for clinging to a rough surface or twig. Tarsal flexion alternates with tarsal extension, which releases the hold for the recovery movement (stepping) of the leg, to produce the actual propulsive movement.

Insects are able to move forward, sideways, and backward. During forward locomotion most insects use legs R1 (right prothoracic), L2 (left mesothoracic), and R3 (right metathoracic) as a tripod support while legs L1, R2 and L3 are raised from the ground. This may be described as (R1 L2 R3), (L1 R2 L3) sequence. Many variations of this sequence may occur in one insect.

MAGNITUDE:

During walking and running in many insects, such as the mantis, the leg in any segment always alternates with the movements of the corresponding leg on the opposite side, and variations in the order of stepping are due to the sequence of pauses between leg movements.

The speed at which insects walk varies to a considerable degree. The stick insect and the cockroach can walk 20 feet in less than 12 sec.

SIMILAR EXAMPLES:

Leg locomotion in man is similar to insect walking movement in the coordinated motion of the legs and their individual sections.

SAMPLE PHYSICAL ANALOGS:

The pistons in an engine are analogous in that they move up and down in an orderly manner, transmitting discontinuous motion to the drive shaft. The discontinuous motion is smoothed by the fly wheel.

REFERENCES: 119, pp. 467-472.

SECTION 10:

MANIPULATION

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BIOLOGICAL ASPECTS OF MANIPULATION

Manual manipulation is a characteristic ability of the higher forms of animal life, specifically mammals. Within the mammalian group itself, this ability to work with the hands and fingers increases in efficiency until its highest stage of development is reached in man.

The human arm and hand possess an exceptional mobility and can be placed in positions that serve to illustrate the changes that have taken place during evolution. The fin with dorsal and ventral muscles, serving to raise and depress it for purposes of steering, became changed into a limb. The limb then has a pre-axial border, occupied by the radius bone and the thumb corresponding to the front of the fin, and a post-axial border with the ulna and little finger.

The mammalian limbs have therefore changed from a condition in which they projected in a lateral direction from the body to being brought under the body for support and elongated to act as levers. The first stage was the bending of the limb at the elbow and the wrist. This stage was already reached in mesozoic amphibians and reptiles. The hand was then adapted to be oriented forwards and the first digit to be medial. The bones are fixed this way in many mammals such as the rabbit. In primates however, the hand can be returned to the more primitive supine position, with the radius and ulna parallel and the thumb pointing laterally.

PHYSICAL ANALOGS IN GENERAL

The history of the invention of manipulative devices is largely a history of man's attempt to extend the manipulative capability of his own hands. It has only been recently that other types of devices have arisen; the impetus for these more recent developments in manipulative devices was largely provided by the introduction of the production line, and the need for handling greater quantities of materials than could men, even with tools.

Material-handling and manipulative devices found on production lines tend to be large, heavy, and usually stationary--a consequence of the concept of a production line as a fixed flow of materials. Still more recently, however, some manipulative devices have been constructed as a direct imitation of man's hand. Modern functional prostheses are an obvious example of this, but the remote handling equipment used for radioactive materials is, perhaps, a better indication of a trend, as yet limited, to more flexible, all-purpose materials handling equipment. Some additional impetus for the development of smaller, lighter, and more capable machines can be foreseen in the requirements for operating in hostile environments, such as in space or under water.

As the demand for greater remote handling capability increases, it will also force additional studies of control of multivariable systems. Beneficial secondary effects of these studies on other parts of industry, such as the production of chemicals, can also be anticipated.

Physical Class	Physical Operator	Section 10
Chemistry Fluid Mechanics Mechanics	Sensors: Contact, Distance Actuators: External	Manipulation

THE ELEPHANT'S TRUNK

DESCRIPTION:

The elephant's trunk is a muscular organ which is an elongated combination of the elephant's nose and upper lip. It is closely associated with the motor and sensory centers in the cortex of the brain. There are two small projections at the end of the trunk which are similar in appearance and function to human fingers. The trunk can be used to perform both feats of strength and delicate sensory and manipulative functions by means of the two end projections.

ILLUSTRATION:

The highly developed sensory characteristics of the trunk enable the elephant to gather information about its surroundings. The sensitivity of the trunk allows it to be used to pick up a sewing needle from the ground, or untie a knotted rope.

The trunk is also quite strong and the elephant can use it to lift objects weighing hundreds of pounds.

MAGNITUDE:

The average trunk is 6 feet long, and weighs 300 pounds. In addition to the highly developed sensory and motor nervous system, there are approximately 40,000 muscles in the trunk. By comparison, the human body has approximately 600 muscles.

SIMILAR EXAMPLES:

The only manipulative organ of an animal that compares with the elephant's trunk in versatility and overall efficiency is the human hand. However, the hands of all the primates, such as monkeys, chimpanzees, and orangutans, are similar.

An octupus tentacle, a mole snout, or the tentacles of the polyp, the sea anemone, and the sea cucumber perform some actions similar to those of the elephant's trunk.

SAMPLE PHYSICAL ANALOGS:

The elephant's trunk is a highly complex system of sensory and motor nerves, muscles, and a combination pneumatic and hydraulic transport system; as such, there are no physical analogs of the entire trunk.

It is possible that an appendage similar to the elephant's trunk would be feasible for an automaton, with manipulation and sensing as the primary functions.

REFERENCES: 4, pp. 53-54; 18, p. 14; 57, p. 520; 60, p. 120; 151, p. 2296; T56, pp. 18-19; 157, pp. 44, 48-49.

Physical Class	Physical Operator	Section 10
Mechanics	Sensors Actuators Contact External	Manipulation

THE HUMAN HAND

DESCRIPTION:

In addition to being a sensory organ, the human hand can be used to grasp, to manipulate, and to participate in some forms of locomotion such as swimming, climbing and crawling.

The skeletal structure of the hand includes the series of 5 metacarpal bones which attach it to the carpal bones of the wrist, and the 5 divergent series of smaller bones (phalanges) located in the fingers. The human thumb is called "opposable" because of its ability to assume a position which is opposite to the 4 fingers, and its flexibility in being able to touch any part of those fingers. The strongest finger and thumb muscles begin in the forearm and are attached to tendons below the wrist. These tendons travel to the fingers and the thumb through tubular sheaths.

ILLUSTRATION:

Movement results from motor activity of the muscles upon the levers of the skeleton. Each contracting muscle generally exerts a mechanical effect which is due to its fixed attachment to the bone lever. The arrangement of muscles and lever arms allows for several types of organization. The most elementary is the hinge joint as involved in the interphalangeal and metacarpal regions. This joint requires the simultaneous and antagonistic action of two muscles on opposite sides of the bone lever for mobility.

The fingers, thumb and wrist have ball joint articulations which allow movement in any direction around the ball center within its angular cone of action. The articulation is mediated by a series of muscles acting in the several planes.

Man possesses an extensive cortical sensorimotor representation of the hand with predominance of the thumb, then of the second and fifth digits.

MAGNITUDE:

There are 27 bones in each hand. Of these, the wrist contains 8 carpal bones, and the palm is made up of 5 long metacarpal bones which connect with each of the fingers and the thumb. Each finger contains 3 phalange bones, and the thumb has 2 bones.

SIMILAR EXAMPLES:

In some monkeys, the prehensile feature of the hand is primary and the thumb is smaller and not opposable.

THE HUMAN HAND, Continued:

The hand of the ape is quite similar to that of man in that the ape also has a great degree of flexibility in his thumbs.

Squirrels and some other animals have manipulative forepaws, as, presumably did the Tyrannosaurus rex and some of the other dinosaurs.

The praying mantis is another example of a creature with grasping appendages.

SAMPLE PHYSICAL ANALOGS:

Prosthetic arms and hands, or double hooks that open and close, are available for amputees. Most life-like artificial hands, called "cosmetic" hands, have controlled thumb, forefinger and middle finger, with the other fingers being "idlers", provided only for the sake of appearance.

Mechanical arms and hands have been utilized for a number of years in nuclear laboratories to handle radioactive materials from a distance. These are operated by remote control to follow the motions of a pair of human hands.

A computer-controlled arm and hand has been designed at the Massachusetts Institute of Technology to assist in the study of artificial intelligence by incorporating into the hand some of the tactile sensitivity of man.

The type of steel cable through which a manual automobile choke control operates the carburetor choke valve is analogous to the arrangement of tendons and tendon-sheaths in the hand.

A complete communications system, including mechanical transport between points of communication would also be analogous.

REFERENCES: 29, p. 25; 32, pp. 1682-1683; 44, pp. 248-250, 512; 57; 88, pp. 4-63; 142, p. 785; 151, p. 3256.

SECTION 11:

NERVE SENSITIVITY

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BIOLOGICAL ASPECTS OF NERVE SENSITIVITY

Nerve sensitivity may be defined as the ability of nervous tissue to react to stimulation. The basic unit of the nervous system is the nerve cell or neuron. Each neuron has many afferent dendrites, which may be considered as input channels, a cell body, and a branching efferent axon or output channel. The junction point at which the axons of one cell body joins the dendrites or cell body of the next neuron are called synapses.

Neurons are either combined in various numbers to form different types of nerves, or they may act individually. When several nerves are grouped together, they form a nerve trunk. A nerve ganglion is a "bundle" of nerves grouped together.

Nerves are divided into three groups:

1. The afferent nerves carry a stimulus from the receptors in the various sense organs to the brain.

2. The efferent or motor nerves carry impulses from the brain, or other nerve centers, to the muscle tissues.

3. The central or adjustor nerves are those in the brain and spinal column, which carry stimuli between each other and between the sensory and motor nerves.

In man, for example, the complete nervous system is made up of three separate systems, each having its specific functions:

1. The central or cerebrospinal system, which is composed of the brain and the spinal cord, forms the main portion, and in a general sense may be considered as the communications center of the animal body.

2. The peripheral nervous system consists of the nerves which come from the central nervous system and lead to the various parts of the body.

3. The autonomic nervous system (involuntary and made up of two subsystems or branches) controls the internal organs of the body. The motor branch keeps the organs in their state of physiological equilibrium, while the sensory branch transmits the sensations such as hunger and thirst.

PHYSICAL ANALOGS IN GENERAL

The most precise physical analogs of living nerve cells are the various artificial nerve cells, or neuromimes, used in information networks. There are two types of such cells:

1. The non-adaptive types, such as the original McCulloch-Pitts threshold-logic model which simulates threshold and pulse-repetition frequencies.

2. Adaptive or learning devices like the Artron, Perceptron, Neurotron, and Babcock's neuron-like elementary unit. Both types of artificial nerve cells can learn as a function of circulating signals in a network, but neuromimes of type 2 can take advantage of the much more efficient type of learning that is found in the neuromime itself.

Some neuron characteristics that have been simulated in neuromimes are observed while others have been postulated. In general, the postulated characteristics have to do with learning, adaptability, and the influence of goals, whereas the observed characteristics have to do with fixed functions such as thresholds and inhibition.

The primary value of fixed function models is in simulating biological parameterization, such as those fixed functions that may exist in the retina of the eye. At the expense of somewhat more complexity, the adaptive function models can serve the requirements of fixed functions, and, in addition, can learn and adapt to the extent of providing generalized learning capability. Neuromimes with a generalized learning capability can be organized by the environment to provide satisfactory results in a wide range of problem situations.

Some of the more significant characteristics of nerve cells from the viewpoint of using simulated neurons in learning automata have been summarized. Neurons can function as logical gates, such as AND, OR, and INHIBIT gates. Neurons have numerous inputs (dendrites) and one branching output (the axon), and presumably may change from one gating function to another with learning. This latter is an essential point, but needs more neurophysiological investigation.

Neurons can be joined into networks, which may involve systematic connectivities as in lower centers such as the cerebellum, or may be joined into networks which may be more randomized in connectivity as in the higher centers of the brain.

The neuron response is largely "all or none", which implies digital operation, although continuous or analog quantities can influence the response repetition rate of the neuron and certain other features of its firing. This results in analog information being coded as pulse density per unit time, as discussed by von Neumann (Ref. 111).

The functions of neurons are apparently subject to learning by a trial and error process. A type of selective action for organizing functions of neurons in the living brain based on "pain" and "pleasure" is discussed by Wiener in his Cybernetics and a form of habit reinforcement is discussed by Hebb in his The Organization of Behavior. The resemblance of such a trial and error process to the natural selection of species has been noted by Ashby and by Lee, and principles of natural selection are incorporated in Ashby's Homeostat(Ref. 3),

and in various Probability State Variable devices developed by Lee (Ref. 86).

Neurons may search function space in the trial and error process as a result of spontaneity in the neuron, which may arise from thermal noise or chemical fluctuations in the blood coming to the neurons. A learning device searches function space and then retains the most satisfactory functions found. A search based upon spontaneity, as may be derived from phenomena such as Johnston noise can be advantageous in machines as discussed elsewhere in this compilation, and may supply the impetus for imagination, creativity, and initiative, when suitably constrained by previous experience. One possible physical analog here is the kaleidoscope, which, with its random element, has actually been used for creative design art. It may be that nerve cells act like biasable kaleidoscopes, in terms of information rather than colored glass, but the increasing organization in a nerve network comes about through a retention of satisfactory information transfer functions that have no counterpart in the kaleidoscope. Such spontaneous nerve impulses have been observed (Ref. 42). These spontaneous impulses may be quite important in understanding some of the more elusive aspects of intelligence in the human brain and for application in machines.

Physical Class	Physical Operator	Section 11
Chemistry Electricity and Magnetism	Transformers Actuators Energy External Information Internal	Nerve Sensitivity

ACETYLCHOLINE TRIGGERING OF MUSCLE ACTION

DESCRIPTION:

Acetylcholine, an active ester of choline, is found in the end branches of a motor nerve fiber. According to many theories of nerve transmission, activity in the nerve terminals causes a release of acetylcholine which then reacts with the muscles, producing a change in them. It is this chemical reaction which then would account for the transmission of impulses. This theory has been validated to a limited extent in that nerve degeneration or other inhibiting treatment of the nerve will decrease or abolish the amount of acetylcholine.

ILLUSTRATION:

A motor nerve fiber is divided into several branches near the end. Each of these branches is connected to a muscle fiber by a small flat plate or motor-end-plate. One of the characteristics of this plate is the delay of a few milliseconds between the arrival of a nerve impulse at the end plate and the resulting contraction of the muscle fiber. During this delay acetylcholine is released, allowing the impulse to travel from the motor end-plate into muscle fiber to cause the contraction. Immediately after the contraction, the enzyme, acetylcholinesterase, hydrolizes the acetylcholine, thereby allowing it to be removed almost instantly. If the enzyme were not present, or its action inhibited, the acetylcholine would accumulate and block the transmission of subsequent impulses.

MAGNITUDE:

The required functional quantity of acetylcholine is so minute that it is difficult to demonstrate chemically. However, the extreme sensitivity of tissue to small amounts of acetylcholine is illustrated experimentally when a solution containing 0.001 mg in one liter of fluid causes the heart of an ordinary clam to react.

It has been estimated that the amount of acetylcholine released from the nerve endings at a simple junction in response to a single nerve impulse is about 10^{-17} moles.

SIMILAR EXAMPLES:

It has been postulated that epinephrine, released at the sympathetic postganglionic endings, accelerates or facilitates the coronary flow in a manner similar to the action of acetylcholine.

ACETYLCHOLINE TRIGGERING OF MUSCLE ACTION, Continued:

SAMPLE PHYSICAL ANALOGS:

Since acetylcholine serves to link the electrochemical signals from nerve cells to the muscle fibers, any device that couples a signal of, say, a digital nature to an actuator provides an analogous function. In this context, a digital to analog converter provides an analog of acetylcholine functioning.

REFERENCES: 5, pp. 949-950, 1101; 7, pp.1304-1305; 30, pp. 210, 230-233,1133; 129, pp. 74, 100, 102.

Physical Class	Physical Operator		Section II
Electricity and Magnetism	Sensors Distance Transformers Information	Actuators External Internal	Nerve Sensitivity

DU BOIS-REYMOND LAW

DESCRIPTION:

According to the Du Bois-Reymond law, the efficiency of an electric current passing through neural or muscular tissue depends on the rate of change in the current density rather than on the absolute strength of the current. Therefore, as the rate of change decreases, the absolute rise or fall in potential must be increased to attain threshold.

ILLUSTRATION:

The strength or intensity of a stimulus is given by the degree of variation in energy potential; for example, it is dependent on the voltage in electrical stimulations and on the rise or fall in temperature in heat stimulus situations. It is the change in the energy level which is primary; the constant phase is effective only during a brief initial period.

For example, the stimulation of a muscle with a galvanic current is illustrative of this fact. There is a contraction at the onset and at the termination of the stimulus but while the current flows at a constant potential, there is no contraction. It is the rise and fall in potential in the two specific instances which act as stimuli.

MAGNITUDE:

Du Bois-Reymond expressed this phenomenon in terms of a law, namely, that excitation, E, is a function of the derivative of the density of current c with respect to time t; $E=f(dc/dt)$.

SIMILAR EXAMPLES:

In terms of visual sensations, an animal must defend itself primarily against hostile motions that are observed as quick changes in the field of view. Similarly, a predator, such as a frog or a flying hawk, looks for motion, that is, sudden change. This effect is then propagated to the visual cortex and the rest of the brain, and may call for sudden muscular response. Thus, in emergency, or in situations calling for quick action, it is the rate of change of signal rather than absolute signal value which counts, and the physiology of neurons and muscle has apparently been adapted to this.

In pattern recognition situations, the tendency to respond to outlines is doubtless due to changes that occur in retinal cells that are near the outlines of patterns. This occurs as the eyeball jitters so that the cell crosses back and forth over the color boundary.

See also "Electrical Response in Nerve and Muscle Cells".

DU BOIS-REYMOND LAW, Continued:

SAMPLE PHYSICAL ANALOGS:

The energy transferred through capacitors, inductors, or circuits combining capacitors and inductors is, in most cases, proportional to the rate of change of the current density.

REFERENCES: 68, pp. 772-773.

Physical Class	Physical Operator	Section II
Acoustics Chemistry Heat and Thermodynamics Mechanics Optics and Light	Sensors Contact Distance Internal Transformers Information	Nerve Sensitivity

MÜLLER'S LAW OF SPECIFIC NERVE ENERGIES

DESCRIPTION:

The theory of specific nerve energies states that each sensory nerve has its own characteristic type of activity. This has been supported to some extent by the fact that a special group of sense organs normally has a uniquely low threshold for a particular stimulus and also, by anatomical arrangement.

ILLUSTRATION:

According to this theory, the optic nerve can signal only visual phenomena, the auditory nerve only the quality of sound, the olfactory nerve that of odor and so on. If, for example, the eyes are turned to the extreme left and pressure is applied to the outer corner of the right eyelid, the resulting sensation involves seeing a dark disk in the extreme left of the visual field. The sensation is visual in spite of the fact that the stimulus is pressure. Similarly, most receptors can be stimulated by an electric current with the resulting sensation being one of touch, pain, light or sound, depending on the receptor area being stimulated.

The nerve impulses themselves, however, cannot account for this phenomenon since they are all fundamentally the same. The critical difference may depend on the localization of these impulses when they reach the various areas of the brain. Evidence for this view is found in the fact that a blow on the back of the head, over the occipital lobe, makes a person see a flash of light.

Another theory places the importance on the pattern of the fibers being stimulated. In the sensation of taste, for example, impulses in one set of fibers will produce the sensation of saltiness whereas when this is combined with activity in all the other types of fibers, the resulting sensation is one of a sour taste.

MAGNITUDE:

Specificity can be substantiated by the varying rates of response as well as by the different sensitivities. For example, there are two types of thermal units in the cat's tongue; in both types the temperature of the receptors determines the frequency of the impulse. However, the maximum frequency in one group is at a temperature of 30 to 32° whereas in the other it occurs at 37.5 to 40°C.

MÜLLER'S LAW OF SPECIFIC NERVE ENERGIES, Continued:

SIMILAR EXAMPLES:

This specificity can also apply to the different properties of the stimulus as well as to the sensory units themselves. For example, mechanically sensitive units do not respond to thermal stimuli or to acid; thermally sensitive units will normally not respond to mechanical stimuli; and furthermore, those units which are sensitive to acid, prick, or burning do not respond to mechanical or thermal stimulation.

Specificity to a particular band of frequencies of a periodic function is another example. The primary units of the retina for instance may respond to different frequencies of light waves and the frequency of sound waves may elicit unique characteristics from the mammalian cochlea. In the latter case it is the mechanical properties of the system which are responsible for the given effect.

SAMPLE PHYSICAL ANALOGS:

Most physical devices used for transduction are quite specific in their sensitivity to different types of stimuli, responding to but one or very few types of inputs. However, the specificity of subjective response of the brain to signals from sensors has no simple, physical counterpart; this is apparently a characteristic of the structure and functioning of the brain.

REFERENCES: 5, p. 962; 30, p. 124; 68, pp. 867-868.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism	Transformers Actuators Energy Internal Information	Nerve Sensitivity

NERVE IMPULSE CONTROL BY ACETYLCHOLINE

DESCRIPTION:

Acetylcholine is the chemical substance found in the end branches of motor nerve fibers. Its release into the area allows an impulse to pass from the nerve endings to the muscle fiber causing contraction of the latter. When the acetylcholine is set free it diffuses down the nerve fibers. Free acetylcholine is unstable and is readily hydrolized to choline and acetic acid by the enzyme acetylcholinesterase, which is present at the ends of the cholinergic nerves.

ILLUSTRATION:

The depolarization of the naked nerve terminal during activity causes the release of a small amount of acetylcholine (ACh). The ACh diffuses across the small gap between the nerve ending and the end plate and reacts with a receptor in the end plate. The ACh-receptor complex acts to increase the permeability of the end-plate membrane to all ions and is quickly destroyed by the enzyme acetylcholinesterase (AChE), which exists in high concentrations in the end-plate regions of the membrane. The membrane potential of the end plate changes toward zero, no matter what the original potential. If the transmitter action is strong enough, and if the muscle membrane is excitable, the end-plate membrane is depolarized to threshold, and an impulse is propagated away from the end plate in both directions.

MAGNITUDE:

The arrival of an impulse at the nerve terminals liberates a minute amount of ACh (about 10^{-17} moles). From studies of the electrical potentials at the end plate, it is believed that the ACh is liberated from a large number (at least 200) sites in the form of small packets or quanta containing a constant number (roughly 1,000 to 10,000) of ACh molecules.

SIMILAR EXAMPLES:

The action of epinephrine on cardiac muscles is similar to the action of acetylcholine on nerve transmission.

SAMPLE PHYSICAL ANALOGS:

Acetylcholine serves as the means by which signals in nerves are conveyed to muscle fibers. It is therefore a communication channel. Physical transfer of signals from control equipment to actuators is normally accomplished by wires.

REFERENCES: 7, pp. 1304-1305.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism	Transformers Energy Information	Nerve Sensitivity

NERVE IMPULSE TRANSMISSION

DESCRIPTION:

A nerve impulse is a travelling wave of chemical and physical reactions involving particularly the surface membrane of a nerve fiber. It is elicited as an all-or-none response.

The energy for the impulse is provided locally along the course of the nerve fiber and not by the stimulus which initiates the impulse. Consequently, the characteristics of the impulse (action potential, speed, etc.) are unaffected by the nature or intensity of the stimulus.

When an impulse travels along a nerve fiber, it can be detected by its effect on the muscle fibers to which it is applied and also by electrical changes in the nerve fiber itself. The action of a nerve impulse sets up a transient variation in the electrical potential between the inside and outside of a nerve fiber that marks the position of the impulse as it travels.

ILLUSTRATION:

When an electrical impulse is applied to and travels along a nerve fiber, movement of ions on the surface causes a change in the nerve. When such a disturbance is very small, it may not cause a reaction, but if it is increased beyond a certain threshold, an explosive reaction, called the spike or action potential, is produced. Beyond this threshold, the impulse is always the same size regardless of the strength of the stimulus. Furthermore, although nerve fibers may possibly be able to conduct impulses in both directions, they are normally unidirectional.

Most stimuli, including those via a receptor, set off a train of successive impulses in a nerve cell, rather than a single impulse. Therefore, different stimuli produce different responses in a nerve fiber by affecting not the individual impulse, but rather the number and frequency of successive impulses in a train of impulses.

In the absence of an impulse, the inside of a nerve is negatively charged in relation to the outside; this difference is termed the resting potential. During the passage of an impulse past any point on the fiber, it changes momentarily to positive. This wave of energy is the most easily detectable and measurable aspect of an impulse.

MAGNITUDE:

The impulse runs without loss of intensity (vigor) through all the branches of that nerve cell. The rate at which an impulse moves in a nerve is usually higher (a) in

NERVE IMPULSE TRANSMISSION, Continued:

warm-blooded animals than cold-blooded ones, (b) in fast moving animals than in those that move slowly, and (c) in larger diameter nerve fibers. For example, the velocity of a nerve impulse may double with a rise in temperature of about 10 degrees.

Motor Nerve Conduction Rates

Animals	Meters per Second
Mammals	30 - 120
Fish	50 - 60
Medullated nerve of dogfish	35
Snakes	10 - 35
Squid (small fibers)	4.3
Squid (giant fibers)	18 - 35
Earthworms (small fibers)	0.6
Earthworms (giant fibers)	10 - 30
Nonmedullated nerve of crabs	1.5

Hodgkin and Huxley, during their investigation of the nervous system of the squid, were able to thread an electrode into the giant axon of the squid from the cut end. With the aid of a galvanometer, they found that the electrode inside the fiber has a resting potential of 80 mv below that of the electrode on the outer surface of the fiber.

SIMILAR EXAMPLES:

A similar action potential occurs in a muscle fiber when it is stimulated.

SAMPLE PHYSICAL ANALOGS:

H. D. Crane's Neuristor has physical properties analogous to nerve impulse transmission. An electrical impulse, travelling through the Neuristor media, derives energy from the media.

An analogy exists between electronic delay lines having different delay times and conduction rates of various nerves.

A multivibrator circuit has characteristics similar to nerve impulse transmission. A triggering signal or impulse above a given threshold will trigger the circuit, which then forms an output pulse.

According to R. S. Lillie, an iron wire placed in a nitric acid bath will acquire a coating that is resistant to

NERVE IMPULSE TRANSMISSION, Continued:

further acid attack. This coating, however, can be broken by scratching, and a wave of new chemical activity is then propagated from the scratch along the wire in a manner somewhat similar to nerve conduction.

REFERENCES: 7, p. 1309; 14, p. 46; 22; 30, pp. 75-76; 116, pp. 587, 661; 129, pp. 98-99; 139, pp. 509-514.

Physical Class	Physical Operator	Section 11
Chemistry Electricity and Magnetism	Transformers Information	Nerve Sensitivity

NERVE NETWORK

DESCRIPTION:

A nerve net consists of a group of interconnected neurons which conduct diffusely and exhibit integrative properties. Conduction is relatively slow and may go in many as well as in one direction. The nerve network makes up the greater part of the nervous system in such groups as the Coelenterata and Echinodermata; it plays a major role in peripheral motion coordination in some annelids and mollusks; and may provide local integration in the visceral musculature of many animals.

ILLUSTRATION:

In coelenterates, the nerve nets consitute a primitive coordinating nervous system having many integrative properties peculiar to more complex systems. Conduction may proceed in all directions. These networks show many facilitation requirements. Investigations with drugs have shown much of the facilitation to be neuronal or neuromuscular. For this reason, lack of or decrease in transmission through a net can be attributed to decreasing facilitation at junctions as the wave spreads out from its original location.

MAGNITUDE:

In the luminescent sea pen Renilla, facilitation is necessary for nonpolarized, non-decremental conduction. The dependence on facilitation varies widely. For example, in the coral Heteroxenia, the response increases upon repetition until the whole colony is involved. In Acropora and Porites a single shock will cause the coordinated contraction of many polyps. In Palythoa on the other hand, there is little spread on repetition.

SIMILAR EXAMPLES:

Single-cell animals, such as amoebae, have no nervous system, and sensing and action functions are provided by more diffuse processes than assemblies of nerve cells.

SAMPLE PHYSICAL ANALOGS:

Some early artificial nerve nets or cell assemblies were presented by McCulloch and Pitts, Beurle, Farley and Clark, Lee (Reron, Artron, Neurotron), Rosenblatt (Perceptron), and Mattson. Other important contributions have been made by Wiener, Hebb, Ashby (Homeostat), Uttley, Stewart (MABIAC), Barlow, Widrow (Memistor, Adaline), and numerous other investigators.

NERVE NETWORK, Continued:

REFERENCES: 116, pp. 617-619.

Physical Class	Physical Operator	Section 11
Aerodynamics Electricity and Magnetism Mechanics	Sensors Contact Internal Transformers Energy Information Actuators External	Nerve Sensitivity

NERVOUS FACTORS IN INSECT FLIGHT

DESCRIPTION:

The nervous system of insects is primarily responsible for the integration of the various motions involved in the wingbeat to produce forces suitable for flying. Although the mechanical relationships are likewise important, flight is nevertheless initiated, maintained, and regulated by the outflow of impulses through the nerves to the thoracic muscles.

ILLUSTRATION:

The nature of wing movement can be modified as the result of sensory stimulation on many parts of the body. Several experiments with decapitated insects have shown the importance of the flow of stimulation from the head to the thoracic centers for the maintenance of flight. These insects were able to show normal tarsal and abdominal flight reflexes although decapitation rendered them less responsive and considerably shortened the duration of their flights. This was attributed to the decrease in excitability of the thoracic motor centers inasmuch as the normal flow of impulses had been eliminated.

Sectioning the connectives at various levels similarly abolishes or inhibits the flying action.

MAGNITUDE:

With the amputation of all tarsi on an insect, making it impossible for it to gain a firm hold, flight frequently cannot be stopped. Insects treated in this way will often continue to beat the wings until completely exhausted, even after they have fallen to the ground.

SIMILAR EXAMPLES:

The control of respiration by the central nervous system in man is similar in that it is a continuous type of major reflex action.

SAMPLE PHYSICAL ANALOGS:

Guidance systems, such as those used to control drone aircraft, missiles and torpedoes provide control analogous to the control of insect flight by the insect's nervous system.

REFERENCES: 119, pp. 648-655.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism	Transformers Energy Information	Nerve Sensitivity

POTASSIUM ACTION ON INSECT NERVE ACTIVITY

DESCRIPTION:

The gradient of potassium across the cell surface of nerve and muscle is closely connected with the phenomena of excitability and conduction. In the insect nerve, demarcation and action potentials decrease as the potassium gradient at the cell surface is decreased by the addition of potassium to the external saline. Insect nerves and muscles lose potassium to the external medium during activity and reclaim it during subsequent inactivity.

ILLUSTRATION:

Potassium ions have complex effects on excitability. Although an increase in the potassium content of the medium outside a nerve fiber appears to depress excitability, this change is preceded by a transient stimulating action. In the crayfish, increased external potassium causes an increase in the spontaneous activity of the nerve cord, which is followed by a decrease or cessation of spontaneous activity if the rise in external potassium is sufficient. A reduction in external potassium may increase spontaneous activity in freshly dissected insect cords, depressing it in older preparations.

MAGNITUDE:

Spontaneous activity and axonic and synaptic transmission in the nerve cord of the cockroach is not immediately affected by changes in external potassium within a range of zero to 50 millimoles which is well above the range tolerated by vertebrate and crustacean nerves. The nerves of Locusta can tolerate 140 millimoles potassium for 2 or 3 hours before conduction block occurs.

SIMILAR EXAMPLES:

Effects on excitable tissue are also derived with calcium and sodium. Calcium most noticeably affects the nerve excitability. An increase in external calcium may cause depression of excitability. The presence of sodium seems to preserve the nerve fibers of vertebrates in a state of normal excitability.

SAMPLE PHYSICAL ANALOGS:

Virus ultrafiltration devices and ion separation devices both are analogous in operation to potassium action on insect nerve activity.

REFERENCES: 119, pp. 452-454.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism Heat and Thermodynamics	Sensors — Transformers Internal — Information	Nerve Sensitivity

REFRACTORY PERIOD

DESCRIPTION:

Each nerve impulse occupies an inch or two of the length of the nerve fiber at any instant. When it has passed a given place along the nerve, that area will not transmit another impulse for a given period. This interval is known as the absolutely refractory period.

Within 1 or 2 ms, the fiber has recovered partially so that a very strong stimulus will elicit a very weak impulse. During this period, referred to as the relatively refractory period, the available energy increases until the fiber is restored to its original state.

ILLUSTRATION:

The refractory period is not due to a change which is limited to the point of stimulation. It follows the nerve impulse as it passes along the fiber. The refractory period will be of the same magnitude and duration all along the fiber. Moreover, if two impulses are transmitted along a nerve in rapid succession, the second one will travel at a subnormal velocity as long as it remains in the relative refractory period of the first.

Following the relatively refractory period is a period of increased excitability, the supernormal period, and following this there is a period of depressed excitability, the subnormal period. These periods seem to be related causally to the durations of the negative afterpotential and the positive afterpotential respectively.

MAGNITUDE:

In a frog's sciatic nerve at a temperature of about 15°C, the absolute refractory period has a duration of between 2 and 3 ms. It is much shorter in mammalian nerve fibers at rates higher than about 1,000/sec.

SIMILAR EXAMPLES:

In nerve or muscle stimulations, the refractory period is over before the contraction is well started. Therefore if either a muscle or nerve is stimulated twice in such rapid succession that the second stimulus falls within the contraction period of the first, the response will increase. This phenomenon is referred to as the summation of contraction.

REFRACTORY PERIOD, Continued:

With the heart however, this is not possible. In this case, the absolutely refractory period lasts throughout the contraction so that a second stimulus applied during the contraction will not have any effect at all.

SAMPLE PHYSICAL ANALOGS:

Integrating circuits, gate circuits, filter circuits, and delay lines all have characteristics analogous to the refractory period.

REFERENCES: 5, pp. 47, 890, 934; 7, pp. 1126-1127; 22, pp. 370-371; 26, p. 239; 86.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism Optics and Light	Sensors Contact Distance Internal Transformers Energy Information	Nerve Sensitivity

SENSORY ADAPTATION

DESCRIPTION:

When a receptor organ is subjected to an abrupt increase in the forces applied to it, and this new level of stimulation is maintained, the sensory unit will discharge impulses at a gradually decreasing rate over a period of time. This decline is referred to as adaptation and may be fast or slow. In order to maintain a constant rate of discharge, the strength of the stimulus would have to be increased continually.

ILLUSTRATION:

The sense of taste exhibits this adaptation characteristic. The continuous flow of a solution over the tongue results in a rise in the absolute threshold. The necessary increase in threshold and the simultaneous decrease in sensitivity are proportional to the intensity of the adapting stimulus.

Insofar as the taste sensation is concerned, it would seem that adaptation is a central process. This assumption is based on observing phenomena such as tha. in which the same peripheral fibers and receptor cells are affected by calcium chloride and sodium chloride, yet no cross adaptation occurs.

MAGNITUDE:

There is a small amount of error adaptation in the case of the sour taste and to a lesser degree in the bitter and sweet sensations. However, in the case of salt, no cross adaptation at all was found for 24 different inorganic salts.

SIMILAR EXAMPLES:

Adaptation studies on the eyelid olinking reflex and finger retraction were conducted with human subjects. Before the main tests, one half of the group received initial stimuli from puffs of air and very weak shocks, while the other half was designated as the control group and received no stimuli prior to the tests. The results showed that prior adaptation of eye blinks reduced the conditioned response frequency among the subjects from 27.7 to 6.0. The frequency of finger retraction responses dropped from 27.1 to 10.

SAMPLE PHYSICAL ANALOGS:

Differentiating circuits and circuits with phase lead have the property that a step input produces a gradually diminishing response analogous to adaptation.

REFERENCES: 1, p. 10. 30, pp. 125, 524-525. 78, pp. 59-60.

Physical Class	Physical Operator	Section II
Chemistry Electricity and Magnetism	Transformers Information	Nerve Sensitivity

STIMULUS SUMMATION AND INHIBITION IN NEURONS

DESCRIPTION:

Stimulus summation generally refers to the additive effect of separate stimuli. In neurophysiology, it is the additive effect of separate impulses arriving at a nerve cell or effector cell. Summation is one of the main ways in which impulses can interact. Therefore, nerve cells functioning together can produce effects quite different from the sum of those due to the nerve cells singly.

Inhibition in neurons is the prevention of activation of the neuron due to the influence of other nerve impulses on it.

ILLUSTRATION:

As a simple example of summation, assume that nerve cell A has synapses with the nerve fibers of nerve cells B and C. Impulses arriving in B or in C alone may not stimulate the production of an impulse in A. However, if impulses arrive simultaneously or very shortly after each other in both B and C, their joint action may produce an impulse in A.

The separation of the summating impulses may be spatial, meaning that they arrive at different synapses on the same nerve cell, or they may be temporal, in which case they arrive successively at the same cell, or both. Many impulses may be involved in any one process of summation.

Whereas summation is a local process, inhibition occurs in the central nervous system. For example, when a muscle is stimulated by its motor nerve fibers to contract, the tonus of antagonistic muscles is simultaneously relaxed by inhibition of their motor nerve cells. This is called reciprocal inhibition. A reflex can also be inhibited by stimulating both the sensory nerve fibers of the reflex and certain other sensory nerve fibers at the same time. Such central inhibition is one of the most important ways in which the central nervous system produces its flexible control over activities by preventing action in unsuitable circumstances.

Peripheral inhibition occurs in Crustacea in which special inhibitory nerve fibers block the neuromuscular transmission of the excitatory impulse in the motor fibers. Similar to excitation, inhibition can summate temporally and spatially.

MAGNITUDE:

The short duration of effect of each nerve impulse fades before the refractory period will allow the next impulse to arrive. The impulses must arrive practically simultaneously if they are to summate since the effective period is less than a half ms.

STIMULUS SUMMATION AND INHIBITION IN NEURONS, Continued:

SIMILAR EXAMPLES:

Summation occurs in muscle action in that if a large number of muscle fibers are stimulated to contract, the resultant force is greater than if only a small number are stimulated.

A type of inhibition occurs in the autonomic nervous system of vertebrates; for example, the vagus nerve inhibits heart beat while the sympathetic nervous system stimulates it.

SAMPLE PHYSICAL ANALOGS:

Logic and threshold devices such as computer components or artificial nerve cells (neuromimes) are physical analogs. A logical "and" gate is the analog of summation, and a logical gate with a function such as $ab' \equiv c$ is the analog of inhibition, where the prime is the logical "not".

A threshold device may require input signals on any "m" out of "n" input channels as a necessary and sufficient condition for having an output where $m \leq n$. It may also require that the sum of weights of stimulated input channels be greater than some threshold value. These functions will give rise to gating functions such as "and" gates, and if some of the weights are negative, will give rise to "inhibit" action.

It appears that such functions in nerve cells should be changeable and adaptable if the nerve network (e.g., cerebral cortex) is to learn. Following this reasoning, the physical analogs of nerve cells for learning systems are typically provided with a means of varying or selecting their minterms, thresholds, and/or weights. Devices developed by Farley and Clark, Lee (Reron, Artron, Neurotron), Rosenblatt (Perceptron), Mattson, and others have such properties. The change is either due to a goal circuit (e.g., Reron, Artron, Neurotron), to a human trainer (e.g., early Perceptron), or to the natural tendency of the networks to gravitate toward a stable equilibrium. Neurotrons also have the capability for learning analog gain and time constants, and as a result of this can provide both minterm selection and threshold selection.

REFERENCES: 1, p. 224; 5, pp. 1011-1013; 7, pp. 1119-1124; 40, pp. 437-450; 83; 88; 108, pp. 72-76; 115.

Physical Class	Physical Operator	Section 11
Chemistry Electricity and Magnetism	Transformers Actuators Information External Internal	Nerve Sensitivity

SYNAPTIC LATENCY AND DELAY

DESCRIPTION:

The onset of response of the electrically excitable membrane depends on the achievement of a critical level of depolarization. Current knowledge indicates that an appreciable irreducible latency or a synaptic delay always precedes a neurally evoked response. Synaptic latency refers to the activity of the presynaptic terminals and the response of electrically inexcitable synaptic membrane. Synaptic delay involves these as well as the utilization time of electrical excitability, i.e., the duration of the depolarization process which is necessary to reach the critical level to evoke a response.

ILLUSTRATION:

The synaptic latency is believed to be compounded from the durations necessary for:

a. release of transmitter from the presynaptic terminals

b. its transit across a synapse, and

c. development of the electrogenic reactions when the transmitter acts upon the postsynaptic membrane.

A strong electrical stimulus which results in rapid depolarization will evoke a response with a very brief latency period. In addition, temporal summation or facilitation may decrease the utilization time and thereby shorten the synaptic delay. The shortening may be a result of a decrease in latency or an increased synaptic excitability.

MAGNITUDE:

A latency of about 0.3 to 0.4 ms exists between the arrival of the presynaptic impulse and the onset of the postsynaptic potential of cat motoneurons. In the eel electroplaque this period is approximately 1 to 2.5 ms.

The utilization time may be as brief as 0.1 to 0.3 ms but can be much longer, depending on the strength of the stimulus.

SIMILAR EXAMPLES:

Reaction time is taken as the elapsed time between a stimulus and a given response on the part of the organism as a whole, for example, the time between seeing a red traffic light and applying the brakes.

SAMPLE PHYSICAL ANALOGS:

Delay in a system, such as rounding and/or delay of the

SYNAPTIC LATENCY AND DELAY, Continued:

leading edge of an impuise in an electronic system would be analogous to synaptic deiay.

REFERENCES: 30, pp. 162-163, 170.

Physical Class	Physical Operator	Section II
Acoustics Chemistry Electricity and Magnetism Heat and Thermodynamics Mechanics Optics and Light	Sensors Contact Distance Internal Transformers Information	Nerve Sensitivity

WEBER'S LAW

DESCRIPTION:

Weber's law expresses the relationship between the strength of the external stimulus and the intensity of the subjective sensation; the least noticeable difference in intensity is proportional to the original stimulus.

ILLUSTRATION:

A comparison of the retinal currents which are evoked by illumination and the visual sensations received by the subject illustrates this phenomenon. Over a limited range of stimulus values, the height of the action current curves varies with the intensity of the light stimulation. At the extremes, however, this law does not hold.

Weber's traditional application of this law involved weight discrimination abilities. Here again, the smallest detectable difference between two weights is a constant function of the weights themselves.

MAGNITUDE:

The threshold varies slightly for different organs, individuals, times, and conditions. The law is not applicable near the extremes of the dynamic range for each sense. Approximate minimum changes discernible are: light, 1%; feeling of weight, 10%; sound loudness, 30%. Fechner formulated the law in mathematical terms as

$$S = k \cdot \log R$$

where S is the experienced intensity, R the physical intensity, and k is a constant for the particular sense. (This is an approximate relationship that holds best through the middle range of intensities, and is often referred to as the Weber-Fechner relation.)

SIMILAR EXAMPLES:

The Fullerton-Cattel law and Breton's law are similar but not identical. Weber's law is essentially the same as Fechner's law, the quotient hypothesis, the progression law (Delboef), and the parallel law. The Fechner-Helmholtz law and "Dark Adaptation" are related.

WEBER'S LAW, Continued:

SAMPLE PHYSICAL ANALOGS:
The logarithmic amplifier is analogous to the biological system.

REFERENCES. 5, p. 1245; 123, p. 306.

SECTION 12:

REGROWTH AND REPAIR

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BIOLOGICAL ASPECTS OF REGROWTH AND REPAIR

Regeneration is the capacity of the organism in postembryonic stages to rebuild organs or body parts that have been lost.

The power of regeneration is widespread among insects and is a property of many organs. If an organ is amputated, the newly formed part usually reappears after the first or second postoperative molt. The exact time of appearance often depends upon the time within the intermolt period at which amputation took place, hence on the time the regenerated organ had at its disposal between amputation and next molt.

Animals such as the coelenterates, Planaria, Nemertina, and Polyzoa are able to partially revise their growth until they are just a fraction of their original size. They can then regenerate themselves completely. Although temperature does affect the rate of regeneration, the organism's nerve supply is the most important factor in the internal regulation among invertebrates.

Among vertebrate animals, regrowth and repair is not as extensive. The more highly developed the animal, the less extensive is the regeneration. For example, the process is limited in reptiles to regrowth of the tail and scales, and healing of wounds in general whereas in birds it involves the replacement of feathers.

In mammals, this characteristic is evident in the healing of wounds and the repair of tissues. Although regeneration of whole limbs is not possible, this system is quite active. Replacement after damage is fairly extensive. A complete liver is regenerated in a mammal even after more than half of it has been removed. Bones become reunited after fracture and are remodeled to meet strains efficiently. Nerves that have been severed are sometimes able to recover their functions.

PHYSICAL ANALOGS IN GENERAL

Much work in the engineering industry is now concerned with systems that are suggestive of tissue regeneration or growth physiology. The growth of transistors or other solid state materials provides examples. This represents growth as a manufacturing process, although an area at least as important is the use of growth to foster a learning process. An important area for growth in future systems is in self-repair, where new components

may be grown to replace old ones. The ultimate in adaptability involves the growing of new and different types of components (self-forming components) as needed to cope with new problems.

Work by von Neumann and by Burks has been done on growing automata at the mathematics and systems levels for computer simulations. Work by Pask, Feldman, and Lee has been done on self-forming or self-structuring devices which are able to grow new functional parts at the molecular level. In addition, the study of synthetic chemical molecules that reproduce themselves has been going on for almost a decade.

We expect that the technology of growing materials will be an expanding and important one in the solid state, electronics, and chemical industries to provide advanced computing equipment, learning automata, and many other products of the coming decade.

Physical Class	Physical Operator	Section 12
Chemistry Mechanics	Transformers Matter	Regrowth and Repair

AUTOTOMY PHENOMENON

DESCRIPTION:

Autotomy permits an animal to rid itself quickly of an injured appendage at a level possessing the highest potentialities for healing and regeneration. Some decapod Crustacea, particularly the Brachyura, have the ability to sever an appendage at a preformed breakage plane by means of a uniseg-mental reflex.

ILLUSTRATION:

Injury to certain portions of an appendage distal to the preformed breakage plane will constitute a stimulus for autotomy. During autotomy in the crab Carcinus maenas, a limb is flexed through the contraction of the anterior levator or autotomizer muscle. Fibers of this muscle have their origin in several regions of the exoskeleton. These are adjacent to the appendage in question and the long slender tendon inserts on the anterodorsal edge of the basi-ischium just proximal to the preformed breakage plane. The segments directly involved with autotomy are the coxa and the fused basi-ischium. During extreme contraction of the autotomizer muscle, the basis slips under the coxa, thus causing the basi-ischium to be pressed against the dorsal rim of the coxa segment. Further contraction of the muscle causes the suture at the preformed breakage plane within the basi-ischium to be sprung on the dorsal side; then the fracture travels ventrally so the limb is ruptured at this level. One fold of a double membrane at the breakage plane is shed with the severed portion of the limb and the other remains attached to the stump.

MAGNITUDE:

All species of crabs can autotomize all 5 pairs of limbs. Within the Brachyura, autotomy has reached its most uniform development. Although in general the response is directly proportional to the degree of stimulation, a delay in autotomy occurs in animals having a thick exoskeleton and sometimes external resistance is neccessary. Animals with a light, brittle exoskeleton usually respond quickly and easily.

SIMILAR EXAMPLES:

Echinoderms can similarly cast off portions of their body. If an arm of a starfish is injured, it may constrict near the base and fall off. A brittle star may cast off an arm piece by piece if pressure is applied first near the tip and then at more proximal levels. The entire viscera of a sea cucumber may be ejected if the animal is disturbed. Within

AUTOTOMY PHENOMENON, Continued:

the vertebrates a lizard may sever its tail near the base if the outer portion is injured.

SAMPLE PHYSICAL ANALOGS:

Although there is no direct physical analog of the complete autotomy phenomenon, many physical devices are constructed with detachable parts that can be replaced if damaged.

REFERENCES: 8, pp. 561-568.

Physical Class	Physical Operator	Section 12
Chemistry Fluid Mechanics Mechanics	Sensors Internal Transformers Energy Matter Actuators Internal	Regrowth and Repair

THE MOLTING PROCESS

DESCRIPTION:

Molting (moulting) is a developmental process among many types of animals in which the outer growth or coat is discarded, and replaced by new growth. Although molting occurs most frequently among many insects during their various developmental stages it also appears in most birds at least once a year, usually starting after the breeding season, in the form of a loss of feathers.

ILLUSTRATION:

As the young insect grows, its outer, chitinous shell becomes tight due to its hard non-elastic state. A molting fluid, which forms between the outer shell and the newer inner layer, acts as a lubricant and partially digests some of the inner surface of the chitinous shell prior to molting. To split the shell and start the process, some insects increase their internal body fluids in certain areas, thereby increasing the pressure on the internal surface of the chitinous shell which causes the latter to tear along the back. The lubrication of the molting fluid facilitates the complete separation of the shell from the insect's body. On exposure to air the soft underskin gradually hardens until it becomes a chitinous shell. At this state of the molting process an insect may not have reached its full size, appearing somewhat shrivelled. Many insects inflate their bodies by swallowing air.

MAGNITUDE:

The frequency of occurrence of the molting process (also referred to as the molt) during insect development varies with different species. Although there are some insects that mature after only one or two molts, others require many more, such as the May fly with 20 molts. One of the most frequently molting insects is the 17-year cicada locust which passes through as many as 30 molts before reaching adulthood.

SIMILAR EXAMPLES:

Molting also occurs among many crustaceans. When a crayfish egg hatches, the larvae emerge from the egg but remain attached to the outer surfaces for two days. After molting occurs, the egg is discarded and a cuticular outer surface is formed on the larval crayfish. Soon this cuticle is loosened and drops off.

In older crayfish, the hard exoskeleton, composed of chitin, is discarded a minimum of 7 times during the first summer of its life. It is within this latter period that the crayfish undergoes the largest amount of growth.

THE MOLTING PROCESS, Continued:

SAMPLE PHYSICAL ANALOGS:

The hard, oxide coating that forms on the surface of aluminum is analogous to an exoskeleton in that it could be said to be protective. (The aluminum oxide coating prevents further oxidation of the metal.) If the oxide coating of a piece of aluminum is stripped off chemically or mechanically, a new coating forms rapidly.

REFERENCES: 48, pp. 235-236; 98, pp. 26-28; 105, p. 1091.

Physical Class	Physical Operator	Section 12
Chemistry Mechanics	Transformers Matter	Regrowth and Repair

REGROWTH BY CRUSTACEA

DESCRIPTION:

Crustacea have the ability to regrow or restore injured or lost parts of their bodies. The speed at which this is accomplished varies with several factors, including the level at which amputation occurred, the extent of damage to tissue remaining within the stump, the stage of the animal in the intermolt cycle, and environmental conditions.

ILLUSTRATION AND MAGNITUDE:

Amputation of a limb from a shrimp produces slight bleeding. This is followed by the formation of a scab, which is sloughed off within several days, revealing a small limb bud. On the sixth day after amputation, a longitudinal furrow appears at the tip of the growing limb bud, and by the ninth day, the first of four annular furrows which delimit the various segments is visible. The limb bud enlarges but, as the intermolt (15-18 days) comes to an end, the regenerate's growth rate decreases. During molt the limb is freed from its protective envelope and appears as a miniature replica of the organ which it has replaced. After successive molts the normal size of the limb is attained.

SIMILAR EXAMPLES:

Regrowth is exhibited by insects, such as Thysanura, Odonata, Orthoptera, Ephemeroptera, Hemiptera, Coleoptera, and Lepidoptera. In general, only regeneration of external parts is possible, although in Lepidoptera replacement of certain internal organs has been reported.

SAMPLE PHYSICAL ANALOGS:

The circuit patterns that can grow into certain configurations in the Adaptive Sandwich developed by R. J. Lee of Adaptronics, Inc. represent one analog. The Adaptive Sandwich is used for learning machine investigations, and the principles of this device may ultimately be of use as a manufacturing process for growing an entire system in a manner analogous to embryonic growth.

Several self-healing devices have been developed using the principle of stored surplus material that can assume the function of another material. As examples, one type of self-healing gasoline tank employs a fluid substance that hardens on contact with the air; in the event of a puncture in the gasoline tank, this substance flows through the hole and hardens on contact with the air, thus sealing the puncture. One self-healing inner tube uses a surplus of rubber on the outer portion of the tire; the surplus rubber is under compression when the tire is

inflated, and, in the event of a puncture, the rubber under compression is forced into the puncture and prevents loss of air.

Oil filled capacitors also possess a minor self-healing characteristic in that arcing due to overvoltage may not necessarily destroy the functional capability of the capacitor.

REFERENCES: 58, p. 392; 87; 114, pp. 232-263.

Physical Class	Physical Operator	Section 12
Chemistry Fluid Mechanics Mechanics	Transformers Energy Matter	Regrowth and Repair

SPONGE REGENERATION

DESCRIPTION:

A sponge is able to regenerate its entire body from a small part of itself although it is an animal of the simplest type, without a recognizable nervous system or other form of physiological control. It grows as a mass of gelatinous tissue, appearing almost amorphous, in its natural habitat of sea water. The natural sponge, with which most people are familiar, is only the supporting framework in which the soft tissue grows.

ILLUSTRATION:

When a sponge is cut into small pieces and each one attached to a rock or some solid surface in a sea water bath, the portion placed on the rock will grow into another animal. If the regrown sponge is pulled away from the rock, leaving only a small piece, again a complete animal will grow from the piece left attached.

When a sponge is forced through a piece of tightly woven cloth or sieve, it becomes a loose mass of separated cells or small pieces of tissue. If these pieces are put into a tank of sea water, they come together, forming the same type of sponge as the original.

MAGNITUDE:

The Florida bath sponge can regenerate from a piece $2\frac{1}{2}$ cu in to one of $12\frac{1}{2}$ cu in in 2 months.

SIMILAR EXAMPLES:

This type of complete regrowth or regeneration is exemplified in the lower forms of animal life such as the Planaria and the one-celled Amoeba. The Planaria has extensive powers of regeneration for a part which may have been separated. A general statement can be made that all forms of animal life are capable of undergoing some form of regeneration. The extent is dependent upon the level of the organism. The lower the form of animal life, the more extensive is the ability to regrow or repair injured or lost parts of their bodies.

SAMPLE PHYSICAL ANALOGS:

See other entries in this section.

REFERENCES: 57, pp. 120-121; 58, pp. 194-212.

SECTION 13:

SOUND DETECTION AND RANGING

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BIOLOGICAL ASPECTS OF SOUND DETECTION AND RANGING

Sound detection and ranging (echo location) may be defined as analysis of intensity, time delay, and phase relationship of reflected signals (echoes) originating at a known location. This technique may be used to detect visually obscured objects. The ability is important to the survival of some animals in allowing current awareness of their changing environment and assisting in a search for food. Animals endowed with this ability include sea mammals, fowls, and bats.

Detection and ranging is accomplished by discrete pulses of high intensity. These are produced by a large larynx, with ossified cartilages which make a rigid framework. The strong cricothyroid muscles put great tension on the light vocal cords. In some cases, for example, the horseshoe bat, there are special resonating chambers and the face is elaborately modified to direct the sound forward. The ear may be specialized accordingly.

Several explanatory theories have been suggested. The most generally favored one postulates that the ear receives both the outgoing and the reflected notes and constructs difference or summation tones by the introduction of a specific nonlinear device. Since the sound is used only for location, its absolute qualities are relatively unimportant. Any object can thereby be located by the variation in the beats which are produced as its position changes.

This distortion is probably a function of the cochlea; it is known to occur in many animals. The auditory nerve then carries information only about the difference notes which is then readily recognized by the brain.

Biological echo location frequencies range from the audible to the ultrasonic with a known upper limit of about 150 kcs for both airborne and water-borne signals.

Some of the net effect of detection and ranging by sound is achieved by the electric sense organs found in some fish. (See the entry "Electric Current Production in Fish.") Changes in electric current densities of currents passing through the fish are produced by nearby objects just as echoes can result from nearby objects. Hence, a form of detection and, possibly, ranging is also accomplished by electric organs. The range over which electric sensing is effective, however, is probably much less than the range achievable by sound.

PHYSICAL ANALOGS IN GENERAL

Sound navigation and ranging (sonar) is used extensively in both submarines and surface craft. It provides a method of measuring distance to the ocean bottom and for the detection and ranging of surface or subsurface craft.

Because of the higher velocity and greater range of electromagnetic radiation, radar is used for somewhat similar purposes in and above the atmosphere.

Many of the basic concepts of sonar and radar are similar, but the wider frequency spectrum used in radar and the greater range of radar detection have led to more elaborate techniques than are used in sonar.

An examination of behavior and of sounds emitted by animals that employ sound detection and ranging indicates that highly sophisticated solutions to the problems imposed by trying to obtain wide-area coverage and high resolution as well as long and short range coverage, are used by animals. Further studies of these animals indicates a well-developed resistance to interference produced by signals emitted by other animals which are very similar in frequency and repetition rate to that of their own signals.

Physical Class	Physical Operator	Section 13
Acoustics	Sensors: Distance, Transformers, Information; Actuators: External	Sound Detection and Ranging

SOUND DETECTION AND RANGING BY BATS

DESCRIPTION:

Bats emit short, sonic and ultrasonic pulses from the mouth. Echoes are received by the ears, analyzed and processed to provide location information of obstacles and food. Duration and frequency of the emitted sounds vary with distance to objects. The mechanism is highly refined to provide discrimination against pulses mitted by other bats. The system used by bats is considered as an amplitude and phase-comparison monopulse system although some bats radiate a frequency-modulated signal.

ILLUSTRATION:

Due to poor visual faculties, the bat relies almost completely upon his echo location mechanism for navigation and ranging. The audible and ultrasonic pulse duration and rate are functions of environment and proximity to an object. Plugging the bat's ears or mouth hinders his ability to dodge fine wires strung across a room and to locate insects. Plugging one ear hinders avoidance of obstacles in the flight path.

MAGNITUDE:

The Eptesicus bat has a maximal acoustic sensitivity between 30 to 40 kcs while most other bats have a maximal acoustic sensitivity at about 10 kcs.

The small brown bat can detect objects of the order of 0.2 mm in diameter.

The intensity of bat emissions ranges from a few dynes/cm^2 to approximately 60 dynes/cm^2.

Myotis bats produce signal pulses of nominal duration of 2.3 ms with the frequency in each pulse varying from 80 kcs down to 30 kcs.

Laboratory tests of the Eptesicus bat yield pulse durations of an average of 3 ms compared to an average of 15 ms in the field.

SIMILAR EXAMPLES:

Some birds, such as the Venezuelan oilbird, Steatornis, and the Asian Swift, Collocalia, combine normal vision with echo location to assist in navigation during darkness. In light, vision is predominatly used, while the utilization of echo location increases as visibility decreases. The emission spectrum observed in birds is not as broad as that for bats. In particular, no ultrasonic frequencies have been observed. Examples of underwater echo location are listed under the entry "Sound Detection and Ranging by Dolphins" in this section.

SOUND DETECTION AND RANGING BY BATS, Continued:

SAMPLE PHYSICAL ANALOGS:

Equipment for the detection of submerged objects and sonar utilize the same principle of navigation and/or ranging employed by bats.

REFERENCES: 47, p. 435; 49, p. 10; 116, pp. 307-308; 132, pp. 227-228.

Physical Class	Physical Operator	Section 13
Acoustics Fluid Mechanics	Sensors Distance Transformers Information Actuators Internal	Sound Detection and Ranging

SOUND DETECTION AND RANGING BY DOLPHINS

DESCRIPTION:

The bottle-nosed dolphin emits complex and varied sounds used in ranging, communication, navigation and food finding. By analyzing the intensity, time delay and phase of echoes the location of objects can be determined.

ILLUSTRATION:

Dolphins emit three types of sounds: sinusoidal whistles, slow trains of buzzing clicks, and complex waves emitted in pulses. The slow trains of buzzing clicks are used in echo location. From analysis of the echoes, dolphins can navigate in turbid water where visibility is poor. In experiments they avoided sheets of transparent plastic inserted into passageways which had previously been used freely.

MAGNITUDE:

Dolphins have a much wider acoustical frequency response than man, with an upper limit of 140 kcs.

The duration of the dolphin's whistle is normally three-tenths of a second with experimental measurement ranging from one-tenth of a second to three seconds. Whistle frequencies were measured from seven to ten kcs.

SIMILAR EXAMPLES:

Whales and porpoise employ underwater echo location for navigation and food searching. As a porpoise nears an object while searching for food, the intensity of the emission increases.

Bats and some birds utilize echo detection in air for navigation and searching for food.

SAMPLE PHYSICAL ANALOGS:

Echo location devices using electromagnetic and mechanical waves are common analogs of animal sound detection and ranging.

Mechanically produced echoes at ultrasonic frequencies are used to determine the distance to the ocean floor in sonar and in devices for locating schools of fish or other submerged objects. Impact point determination in the ocean is accomplished by analysis of time of arrival of the echo at several known monitoring points.

The echo location principle is used in aids for the blind, geological mapping, and geodetic surveying.

Electromagnetic wave echo location is used in radar and surveying equipment.

SOUND DETECTION AND RANGING BY DOLPHINS, Continued:

REFERENCES: 89, p. 63; 90, p. 1689; 91, p. 1873.

SECTION 14:

SOUND PRODUCTION

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BIOLOGICAL ASPECTS OF SOUND PRODUCTION

Most members of the animal kingdom produce characteristic sounds, many of which are stimulated by and centered around special drives.

In man there are three parts which make up the apparatus necessary for sound production: a force that puts a vibrating mechanism into action; the vibrating mechanism itself; and a resonator that reinforces certain vibrations. The force is given by the blast sent through the trachea by the lungs which act as a bellows; the vocal cords form the vibrating mechanism; and the resonator is made up of all the supraglottic cavities, that is, the upper part of the larynx, the pharynx, the mouth and the nose. Sound is produced by the blast passing through the glottis. Immediately before speaking, the glottis is closed and the abdominal and thoracic muscles compress the lungs, increasing the pressure in the respiratory tract. When the pressure reaches a certain level, the glottis opens and the voice is emitted.

The intensity or loudness of a noise is proportional to the amplitude of the vibrations of the vocal cords, which increase with the force of the expiratory blast. Loudness of voice is measured in decibels. There is a difference of approximately 100 db between the softest whisper and loudest cry. In ordinary conversation, loudness of voice varies between 40 and 50 db.

PHYSICAL ANALOGS IN GENERAL

The production of acoustic vibrations by physical devices generally involves strings, rods, membranes, or air columns driven by some suitable means. Resonant cavities are sometimes used to enhance the sound within given frequency ranges. Practically all of the techniques for producing or acoustically amplifying sound used by man are found in living creatures. For example, in creatures with vocal cords, the throat and mouth constitute an air column that is acoustically driven by the vibrations of the vocal cords. The vocal cords themselves behave more as strings than membranes due to muscular tension at the edge of the cords. Resonant cavities in the throat and nose provide distinctive overtones to the sound.

Insect noises (stridulation) are produced by what is physically a stiff membrane driven by a sawtooth-edged rod.

Although the ordinary loudspeaker is capable of producing a good imitation of complex sounds such as the human voice, it is basically an elastic membrane and constitutes an analog of the sound producing mechanisms of animals only in a superficial way.

Physical Class	Physical Operator	Section 14
Acoustics Heat and Thermodynamics Mechanics	Sensors Distance Transformers Information Actuators External	Sound Production

SOUND PRODUCTION IN INSECTS

DESCRIPTION.

Insects usually produce sounds by stridulation, or the rasping of one skeletal structure over another. The sounds may be very complex and compounded by resonance frequencies, sometimes ultrasonic, superimposed on the impact frequency of the scraping structures.

The sounds produced by insects are highly specific, often of social significance such as serving to bring together the two sexes of a species. In most cases the male is the primary sound producer, but females may also respond in a similar manner with sound.

ILLUSTRATION:

In cicadas a cuticular diaphragm is vibrated at high frequency by tightening or relaxing the abdominal muscles. The males of six cicada species, for example, show distinctive sound patterns which serve to isolate each species for sexual attraction. The sounds differ for such social factors as group chorus, courtship and alarm.

Among locusts (specifically the common species known as Melanoplus femur-rubrum) the males produce sounds by rubbing a row of spines on the inner surface of the femur of the metathoracic leg against the outer surface of the tegmina. During flight they can also produce this sound by rubbing the upper surface of the anterior edge of one hind wing against the undersurface of the other.

The male katydid produces a special rasping call sound by rubbing together the covers of its wings which have certain modified veins and cells. They will produce their regular sounds with no particular pattern of repetition. However, if a number of these male katydids are relatively near each other and one hears another sing, they are all attracted by one another's sounds and begin to "sing" in concert. The singing of katydids can be induced by appropriate artificial sounds. This reaction seems to illustrate the importance of these sounds in the communal life of katydid colonies.

In male crickets the stridulating apparatus is highly differentiated. It consists of a file on the base of one tegumen and a scraper on the other. When the wings are held up over the body vertically, the file is rubbed over the scraper causing the wings to vibrate. This produces the characteristic chirping sound. When a number of male crickets are in the immediate vicinity of each other, they chirp in unison, causing a continuous pulsating and relatively loud "racket" similar to that of the katydids. Male crickets are attracted to the female crickets

SOUND PRODUCTION IN INSECTS, Continued:

by the latter's rasping sounds.

Numerous types of flying insects also produce their characteristic sounds by beating their wings together. In the mosquito, for example, these sounds serve to attract the males and females to each other.

MAGNITUDE:

The sound pulses emanating from the noise of insect muscular vibration usually range from 3,700 to 4,200 cps. Some classes of insects produce stridulation sounds above the audible range for the human ear. In the locust, Locusta migratoria, the sound of the pulse rate may rise to 14,000 cycles.

The rate at which crickets produce their chirps depends on the temperature of the air around them. This mechanism is so accurate that a mathematical formula has been derived to determine the temperature by means of the number of chirps per minute. For a more detailed explanation of this process, see the entry on "Thermal Influence on Animal Behavior".

SIMILAR EXAMPLES:

Sound production by stridulation has been observed in Crustacea also. As in crickets and grasshoppers, a crenated ridge on the exoskeleton is rubbed perpendicularly against ridges elsewhere on the body surface. In the marine crab Matuta, sound has been compared with the noise produced when a nail is moved to and fro along a file.

SAMPLE PHYSICAL ANALOGS:

Sounds produced on string or wind musical instruments are analogous to stridulation-produced sound in insects.

REFERENCES: 2, p. 153; 20, pp. 102-103; 116, pp. 311-312.

Physical Class	Physical Operator	Section 14
Acoustics Fluid Mechanics Mechanics	Transformers Energy Actuators Internal	Sound Production

VOCAL CORDS AND VOICE IN HUMANS

DESCRIPTION:

Vocal cords are the mucous membranous bands or folds in the larynx by which the sounds of the voice are produced when the breath passes between the edges of the folds. The true vocal cords are inserted in the angle formed by the thyroid cartilage. They are directed horizontally and backward, ending by insertion on the median or vocal process of the arytenoid cartilage.

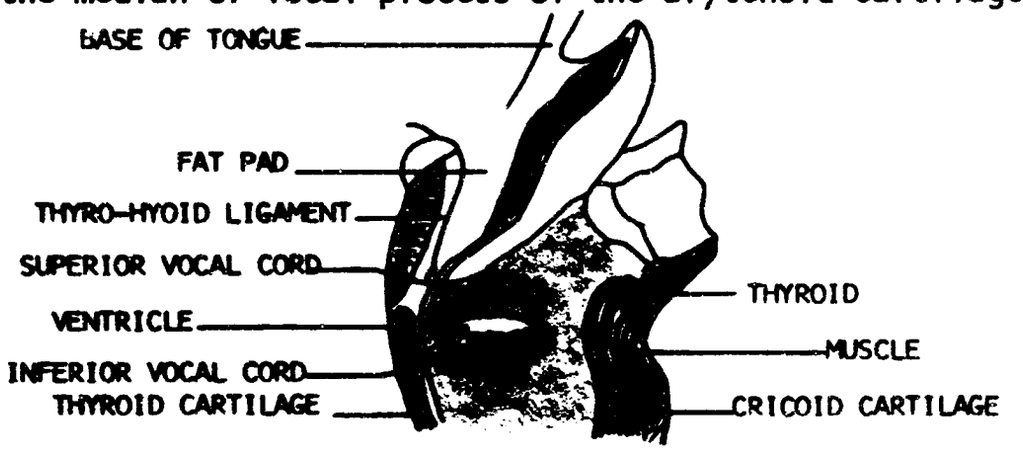

FIG. 21 VOCAL CORDS OF THE HUMAN

ILLUSTRATION:

Sound produced by the human cords follows a sequence of three steps. The first is forcing a vibrating mechanism into action. The force is produced by the sudden flow of air from the lungs through the trachea, with the latter acting as a bellows. The second step is the vibrating of the vocal cords. The third is the resonating of the supraglottic cavities, i.e., the upper part of the larynx, the pharynx, the mouth, and the nose, reinforcing some of the frequencies of the sound produced by the vocal cords.

MAGNITUDE:

The volume and intensity of sound depend on the frequency of its vibrations and the number of tones. These vary with the age and sex of the human. The pitch of the voice depends on the length and tension of the vocal cords. If the vocal cords are suppressed, the noise is toneless.

The frequency range of the newborn is limited to approximately three semitones, increasing as the child grows to include both higher and lower tones. The highest frequency attainable

VOCAL CORDS AND VOICE IN HUMANS, Continued:

by the human female increases until about the 11th year, decreasing thereafter. The highest frequency attainable by the male increases until just prior to or at puberty, at which time both the highest and lowest frequency attainable drop by about one octave. A similar, but much smaller, drop occurs in the female voice at this age. The normal voice pitch and range continue to drop slowly with age in the adult.

The range in pitch in ordinary conversation is usually no more than half an octave. The normal range of the human voice covers about four octaves, the male voice covering 2 1/15 octaves of the lower part of the range and the female voice covering 2 1/15 octaves of the higher portion of the range. There is an overlap of 2/15 of an octave in the middle of the scale.

SIMILAR EXAMPLES:

Parrots and porpoises are able to imitate the human voice. The porpoise imitation is at a higher speed and pitch. It has been reported that an ape has been taught to say several words in proper context.

SAMPLE PHYSICAL ANALOGS:

Speech synthesizers of various types have been constructed, but most of these devices employ physical principles quite different from those of the human vocal apparatus. For example, some speech synthesizers utilize artificially generated formants, while others use a weighted sum of the outputs of oscillators of uniformly spaced frequencies.

One device to produce high intensity sound by means similar to the human vocal apparatus has been reported. This device consisted of a plenum chamber, a pipe containing a flexible, controllable constriction similar to vocal cords, a resonator, and horn to acoustically couple the sound generator to the atmosphere.

REFERENCES: 68, pp. 1002, 1007, 1008; 142, p. 1536.

SECTION 15:

SOUND SENSITIVITY

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BIOLOGICAL ASPECTS OF SOUND SENSITIVITY

The ability to receive and interpret sound stimuli varies greatly among the members of the animal kingdom, and appears to depend on its relative importance in the animal's life.

From a purely physiological viewpoint, man does not hear as well as many other animals. For example, man can hear sound frequencies within the range of approximately 20 to 20,000 cps. However, dogs can detect sounds in the vicinity of 30,000 cps.

Sound localization is another aspect of the overall sensitivity of the organ. There are three widely accepted facts which must be taken into account:

1. Localization is greatly improved with two ears rather than with only one.

2. Animals frequently make mistakes about "above" and "below" or about "forward" and "backward", but rarely about "right" and "left".

3. Noise is more easily located than a pure tone.

The theory which is popularly accepted as explaining these facts depends on the difference in the time of arrival of a sound at the two ears.

In addition to the variation in sound sensitivity among animals, the anatomy of the hearing organ and its location on the animal's body differ considerably. The grasshopper "hears" sounds by means of two tympanic membranes, one on each side on the surface of the middle of its body, whereas in man and many other animals, the organ of hearing is imbedded in the bony structure of the head.

PHYSICAL ANALOGS IN GENERAL

The analogs of mechanisms that produce sound sensitivity in animals can be thought of as consisting of two distinct parts: a transducer (corresponding to the specialized cells that produce electrochemical signals in response to sounds) and a "property" abstraction or parameterization device (corresponding to nerve pathways and, very likely, some of the sensory portions of the brain). The total perception process is quite complex and composed of many specialized processes.

The more obvious physical analogs of the auditory transducers are various types of microphones: crystal, magnetic, carbon, etc. However, microphones are at best very crude analogs of the auditory or vibratory sensors in animals inasmuch as the sensors in animals often provide a significant part of the parameterization of signals. For example, the cochlear coil acts in some respects like a standpipe: nodes of standing waves fall on different portions of the cochlea for different frequencies. Tiny hair cells produce signals in response to the local acoustic environment within the cochlea; hence, some spatial separation of different sound frequencies is provided by the cochlea. Thus, a part of the analysis of auditory signals is provided by the structure of this organ. As a minimum, it would take a combination of a sensor, such as a microphone, and a bank of filters to simulate the functional characteristics of any of the auditory (or vibratory) sense organs in animals.

We can infer from the structure of various types of sound receptors (and from their apparently different functional characteristics) that the decomposition of sounds is not the same in all animals. Loosely speaking, then, if we think of sound detection in human beings as an auditory sense, we might say that some animals have a non-auditory sonic sense. In any event, whatever the nature of the sound or vibration detection organ, the mechanisms of sound decomposition found in animals are often quite different from those used by engineers, and in some cases it has been simpler for us to describe a possible analog (one not acutally existing) than to describe an existing, but only remotely similar, analog.

Physical Class	Physical Operator	Section 15
Acoustics Fluid Mechanics	Sensors Distance	Sound Sensitivity

THE COCHLEAR COIL AND ITS ROLE IN HEARING IN MAMMALS

DESCRIPTION:

The cochlea is an aperture of the inner ear. It forms the anterior part of the labyrinth, is conical in form, and is placed almost horizontally in front of the vestibule. Its apex is directed forward and laterally with a slight inclination downward toward the upper and front part of the labyrinthic wall of the tympanic cavity. The base of the cochlea corresponds with the bottom of the internal acoustic meatus. It is perforated by numerous apertures for the passage of the cochlear division of the acoustic nerve.

According to Prosser, the current theory of stimulation of the nerve endings in the cochlea is explained as follows:

a. The endocochlear and intracellular potentials provide a battery with an electromotive force (emf) of 150 mv across the hair-bearing ends of the hair cells.

b. The magnitude of the measured potential varies with the displacement of the basilar membrane and consequent bending or shearing of the hair cells; this change constitutes the cochlear microphonic and the summating potential.

c. The movement of the hairs is assumed to alter their electrical resistance so that current flows.

d. The change of potential is due to the change in voltage drop across the membrane.

e. Slight mechanical deformation of the distal processes of the hair cells causes a valve action by changing membrane resistance, permitting the generator potentials to appear and allowing a flow of current.

The alternating microphonic potential is an alternating voltage produced by the hair cells of the cochlea, particularly the external cells, in response to sound.

When the ear is stimulated by sound, this cochlear monophonic potential is generated in the cochlea and can be recorded easily from the round window. This microphone response is apparently caused by shear forces due to the tectorial membrane over the hair cells.

The summating potential is a direct response of the cochlea to a tone and emanates from the internal hair cells in the following manner: the hairs arising from these cells undergo a bending or shearing motion which results in their asymmetrical displacement and also the production of the summating potential.

THE COCHLEAR COIL AND ITS ROLE IN HEARING IN MAMMALS, Continued:

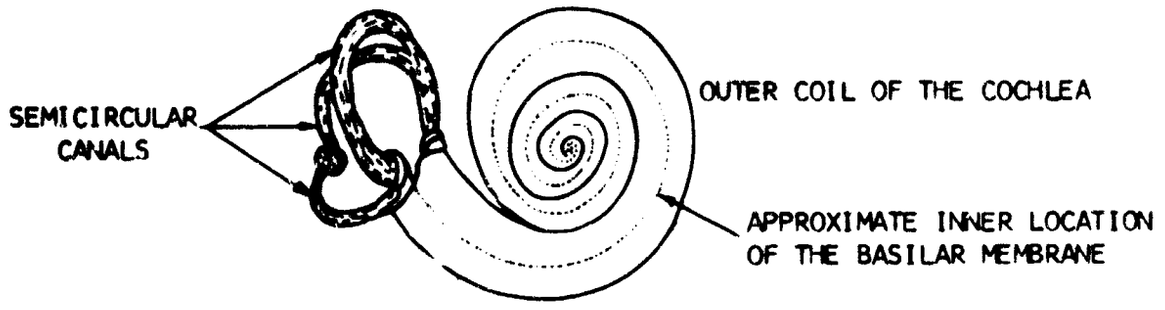

FIG. 22 THE COCHLEAR COIL AND SEMICIRCULAR CANALS

The endocochlear potential of the DC type exists in the electrically positive endolymph of the scala media with respect to surrounding tissue and perilymph. It combines with the negative potential of the cells surrounding the scala media.

The endolymph of the scala media has a positive charge of about 80 mv with respect to the surrounding tissue.

The cells surrounding the scala media like the other tissue cells are internally negative by about 70 mv. Therefore, a total potential of 150 mv exists between the interior of the hair cells and the endolymph. This is an emf of 150 mv across the hair-bearing ends of the hair cells.

ILLUSTRATION AND MAGNITUDE:

The cochlea is coiled only 1/4 turn in the duckbilled platypus, 1.5 turns in the whale, 2 in the horse, 2.75 in man, 3 in the cat, and almost 4 turns in the pig and guinea pig.

An audiogram of man's cochlea shows that he has maximum sensitivity in the range from 800 to 2,500 cps with an upper limit of approximate 16,000. Good audiograms for other animals have not always been obtained with sufficiently pure tones to make a very accurate comparison. The audiograms of animals are generally similar to those of man but exhibit higher thresholds. There are also indications that animals hear at higher frequencies.

Certain dogs can hear up to 35 kc; rats and guinea pigs to 40 kc. A cat's threshold of hearing from 100 to 3,000 cps is close to man's, but from 3 kc to 15 kc it is lower than man's. By observation of the reflexes of parts of the ear, it was found that a variety of small animals, especially mice, can hear in the wide range of 6 kc to 93 kc. For example, a dormouse, Muscordinus, had a minimum threshold at 20 kc, while a deermouse was conditioned over the range of 10 to 65 kc.

Cochlear potentials have also been recorded from the ears of the kangaroo rat, Dipodomys, over a range of 100 to 20,000

cps, with a maximum sensitivity from 2,000 to 4,000 cps.

SIMILAR EXAMPLES:

Although the cochlear coil does not appear in insects, the transduction of sound into nerve impulses is also effected in insects by hair cells. (See "Sound Reception in Insects".)

SAMPLE PHYSICAL ANALOGS:

The overall effect of the cochlea is analogous to the production of standing waves in a standpipe or in a transmission line. An artificial ear has been designed on the basis of this analogy.

The alternating microphonic potential, produced by fluid shear forces acting on the hair cells, suggests a possible sensor that might have some value in air flow studies: Stiff bristles attached to a suitable transducer and placed in a regular pattern over an airfoil could provide electrical signals roughly proportional to local wind velocity.

REFERENCES: 24, pp. 143-154; 68, pp. 985-996.

Physical Class	Physical Operator	Section 15
Acoustics Mechanics	Sensors Distance Transformers Energy Information	Sound Sensitivity

THE ORGAN OF HEARING IN MAMMALS

DESCRIPTION:

The organ of hearing in mammals consists of three distinct parts.

The external auditory canal is the external passage-way leading to the middle ear. The walls of the outer third of the canal is bony and forms a projecting tube from the temporal bone in which both middle and inner ears are housed. The skin lining of the auditory canal is supplied with wax (cerumen) glands and outward-projecting hairs, both of which serve as dust arresters.

The middle ear, or tympanum, is an irregular air-filled chamber in the temporal bone between the external auditory canal and the inner ear. The dorsal recess of the tympanum is the epitympanum, which communicates with the spongy mastoid cavities in the blunt mastoid process of the temporal bone. The eustachian tube below opens into the pharyngeal cavity.

The tympanic membrane, known as the ear drum, is stretched across the circular auditory canal. It is arranged obliquely across the canal, thereby creating a larger receiving surface to be exposed to impact of vibrations

Three bones in vertebrates form a chain from tne inner surface of the ear drum to the fenestra vestibuli, the membrane separating the middle ear from the inner ear. The hammer, or malleus, is attached to the ear drum, the stirrup, or stapes, to the fenestra vestibuli, and the anvil or incus is in the middle and connects the malleus to the stapes. The function of these bones is to transmit the sound waves through the middle ear after they intensify the waves and decrease their amplitude.

On the face of the tympanic wall opposite the ear drum and next to the inner ear are two "windows," the fenestra vestibuli and the fenestra cochleae, both of which are covered by drum-like membranes similar to the ear drum. These cause the middle ear to resemble a hollow drum with very small membranous heads at the two ends.

The inner ear is composed of extremely delicate cells surrounded by fluids and is buried in the dense temporal bone. This closed exodermal sac, called the membranous labyrinth, is filled with endolymph fluid and surrounded by the bony labyrinth. The membranous labyrinth consists of:

a. the utricular region, in which are the statoreceptors or semicircular canals, and

b. a sacular region; in mammals, including the cochlea.

The scala media, which is the cavity in the membranous labyrinth, contains rows of differentiated cells, supported on a basilar membrane, and extending lengthwise to the tip of the cochlea. These cells form the organ of Corti, which is the hearing

receptor apparatus. The organ of Corti is formed by orderly rows of differentiated cells running lengthwise to the tip of the cochlea. In man, the most important cells of this organ are the 5 rows of hair cells which are the phonoreceptors proper and which are connected to neurons of the auditory nerve. The latter transmits the vibrating stimuli to the auditory centers in the temporal lobes of the cerebral cortex. In the human ear there are from 13,000 to 54,000 hair cells (estimated) with each hair cell having 40 cilia or hairs at the receptive end projecting into the endolymph. The hair cells all increase in size toward the tip of the cochlea.

A second sound-conducting path to the inner ear exists directly through the bones of the skull, by-passing the outer and middle portions of the ear. Bone conduction thus furnishes a method of testing the physiological status of the cochlear mechanism in patients with middle ear damage. Barany and Bekesy have shown that there are two forms of bone conduction:

a. Inertia bone conduction, in which the skull moves as a rigid body at lower frequencies, occurs if a vibrator is placed against the skull. In this case, although the ossicles do not move, the cochlea does receive the vibration.

b. Compression bone conduction occurs during higher frequencies, where the skull vibrates in sections rather than as a rigid body.

Inertial bone conduction occurs when the vibrator is moving at a frequency below 800 cps. At higher frequencies the compression type occurs. Here all the parts of the ear vibrate as separate units.

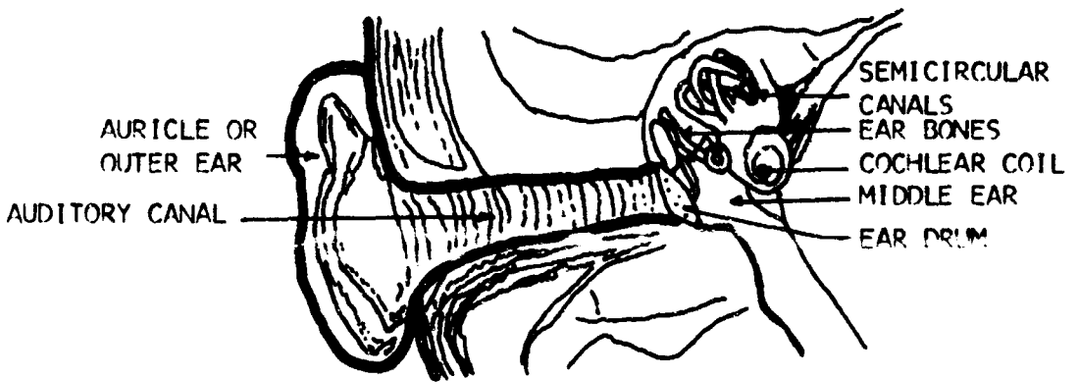

FIG. 23 THE HUMAN EAR

ILLUSTRATION:

The auditory canal serves to convey sound waves to the ear drum and affords, in some measure, protection for the middle and inner ears. After sound waves are received by the outer ear, they pass through the canal and hit the tympanic membrane which

is caused to vibrate. This vibration is transmitted through the membrane to the middle ear, where it is picked up by the chain of 3 small ear bones and passed on to the inner ear. Since one of the three bones, called the stapes, is attached to the fenestra vestibuli, it acts like the plunger of a piston in transferring the sound waves by a thrust to the inner ear. Within the inner ear, sound waves are converted to nerve impulses by the organ of Corti.

MAGNITUDE:

In man, the outer ear is about 2.5 cm long and is slightly bent. It is larger at either end than in the middle. The tympanic membrane is about 10 mm in diameter and about 1 mm thick but is slightly thicker at the center than at the margin.

Sound intensity may be expressed as sound pressure level in dynes/cm^2 but is usually expressed in decibels which give the logarithm of the ratio of the two pressures. The human threshold is usually considered as the reference level for the logarithmic decibel (db) scale of sound intensities. The frequency range to which the normal human ear is sensitive extends from 20 to 20,000 cps and covers about 10 octaves. Sylvian and White at the Bell Telephone Laboratory conducted audibility threshold tests among young adult human subjects and found that the region of greatest sensitivity lies between 2,000 and 3,000 cps. This is also the region of the broad resonance peaks of the external canal. Here the threshold is 6 to 8 db below 0.002 dyne/cm^2 or 0.0001 dyne/cm^2 or less. It was also determined that at 15,000 cps and 100 cps the threshold intensity is approximately 40 db higher than at 3,000 cps. According to an extensive survey by the US Public Health Service, only 1.0% of the population can hear sounds beyond these levels. These values represent very sensitive ears having almost ideal hearing. However, about 50% of the population can hear the sound represented by the limits of 8 and 52 db.

Frequency discrimination, which is better at medium and high intensities, is due in part to difference in the position of the maximum of displacement. High tones activate only the basal turn of the cochlea, while its apex is most sensitive to the lowest tones. Records from single fibers of the auditory nerve have shown fairly sharp limits of cut-off toward the higher frequencies. Generally, fibers arising near the beginning of the basal turn of the cochlear coil respond only to higher frequencies, while fibers near the inner end of the coil respond to the lower frequencies. Both primary and secondary neurons respond to only a narrow band of frequencies at threshold and a wider band at higher intensities. However, each point along the membrane shows maximal movement and also stimulation at a particular frequency. At 60 db, a man with normal hearing can recognize about 1,800 tonal differences.

Most dogs are able to detect sound frequencies which would

be entirely inaudible to the human ear. Certain types of dog whistles seem to produce a sound inaudible to man but completely audible to the dog. Cats are also known to respond to higher tones than are perceptible by human ears, thus in some respects the cat has a relatively well developed auditory system. For additional magnitude information, see "The Cochlear Coil and Its Role in Hearing in Mammals".

SIMILAR EXAMPLES:

In fish, the inner ear is related to the lateral line organ in its ontogeny, in the hair cell nature of the sensing elements, and in the spontaneous activity in the sensory nerves.

Bony fish have been extensively studied by conditioned reflex techniques with respect to hearing threshold, range and pitch discrimination. In general, the Ostariophysi hear better than other fish. They have a set of bones, the Weberian ossicles, connecting the swim bladder with the inner ear. The gas of the swim bladder imposes an acoustic discontinuity in the sound path, and the ossicles provide coupling to the sensing elements. Little loss resulted from injury to the utriculus but when the sacculus and lagena were also damaged, reactions remained only to low tones.

SAMPLE PHYSICAL ANALOGS:

The outer, middle and inner ears, exclusive of the phonoreceptors, serve to parameterize sound waves by mapping sound frequency onto various regions of the inner ear. The phonoreceptors transduce the parameterized sound waves into nerve impulses. Although several physical devices have been constructed that perform the functions of the ear, none of these devices is structurally similar to an actual ear. One of the more functionally realistic devices operates on electrical signals after the sound has been transformed rather than before as in the ear.

REFERENCES: 7, pp. 1435, 1451; 24, pp. 143-154; 68, pp. 985-986, 1000; 116, pp. 304-305; 144, p. 21.

Physical Class	Physical Operator	Section 15
Acoustics Electricity and Magnetism Fluid Mechanics	Sensors Distance Transformers Information	Sound Sensitivity

SOUND RECEPTION IN BIRDS

DESCRIPTION:

In birds, there is a distinct cochlea, slightly curved, and especially well-developed in owls and in parrots. This cochlea has a basilar membrane, with fibers increasing in length towards the tip, carrying an organ of Corti with hair-cells in contact with a tectorial membrane. At the tip of the cochlea is the lagena, a special sensory region, which is similar to that of lower vertebrates and perhaps responsible for reaction to lower notes.

ILLUSTRATION:

Birds are more sensitive to low-frequency vibrations than is man. Transmission of vibration from the tympanum to the inner ear is effected by the columella auris, derived from the cartilagesof the hyoid arch. The inner portion of the columella is rod-like (stapes), but the outer end makes contact with the tympanum by means of three somewhat irregular processes.

Hearing is acute and songbirds, for example, can discriminate between simple tunes. Ability to localize sound is high; owls and other night birds probably find their prey largely by ear. For the purpose of direction finding, they have developed an asymmetrical arrangement of the ear cavities or asymmetrical external ears.

MAGNITUDE:

In pigeons the cochlear microphonic potential (CMP) follows sound up to a limit of 25,000 cps with lowest threshold at 3,200 cps.

Conditioning experiments have shown that parrots and crossbills hear and discriminate well over the range of 40 to above 14,000 cycles.

Pheasants hear up to 10,500 cps with their lowest threshold at 6,000 cps.

SIMILAR EXAMPLES:

Many types of songbirds were conditioned best at about 3,200 cps, and they also responded to vibrations of 100 to 3,200 cps with a maximum sensitivity at 800 cps. This sensitivity to low frequency persisted after the ear was destroyed experimentally.

SAMPLE PHYSICAL ANALOGS:

See the general comments on the physical analogs of the hearing organs at the beginning of this section. Also, see the physical analogs suggested in the entries on "The Organ of

SOUND RECEPTION IN BIRDS, Continued:

Hearing in Mammals" and "Sound Reception in Insects".

REFERENCES: 35, pp. 99-100; 116, p. 307; 131, pp. 35-48; 138, pp. 122-125; 151, pp. 488-489; 155.

Physical Class	Physical Operator	Section 15
Acoustics Fluid Mechanics	Sensors Distance	Sound Sensitivity

SOUND RECEPTION IN INSECTS

DESCRIPTION:

Insects receive sounds by means of tactile hairs and tympanic organs. The latter occur in different families of Orthoptera, Hemiptera, and Lepidoptera. A tympanic organ consists of 2 parts: (a) a thin cuticular membrane associated with tracheae or air sacs that are often protected by a fold in the exoskeleton, and (b) groups of chordotonal sensilla (sensory hairs) attached either to the tympanum or to the associated tracheae. Other chordotonal organs, separated from tympanic membrane, are located on pliable regions of the cuticle. The chordotonal organ contains a number of scolopidea, each with a distal cap cell surrounding a sense rod attached to the terminal filament of the sense cell. The terminal filament is surrounded by a sheath cell, and the nucleus of the sense cell is at the base of the scolopidium.

The organ of hearing in the grasshopper consists of a tympanic membrane tightly stretched within an almost circular ring over a slender point that is connected to sensory nerve fibers. There is one located on each side of the tergite of the first abdominal segment.

Johnston's organ is found in the pedicle of the antenna of male Aedes aegypti mosquitoes. When a sound is received by either the tympanic membrane or Johnston's organ, those hairs which do not have nerves attached to them set a flagellum in motion which amplifies the sound to stimulate the chordotonal organ.

In the noctuid moth, each sensillum (sensory hair) of the tympanic organ contains 2 scolopes (sense cells) which differ in threshold.

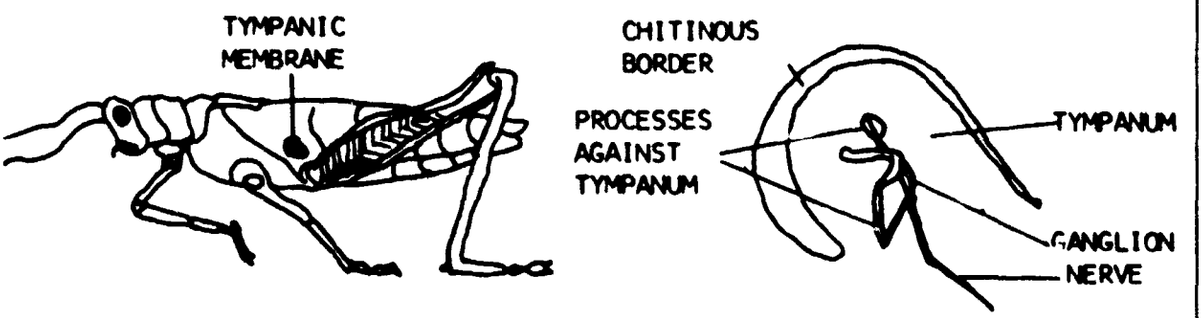

FIG. 24 THE GRASSHOPPER'S SOUND RECEPTOR ORGAN

SOUND RECEPTION IN INSECTS, Continued:

ILLUSTRATION:

The grasshopper ears sounds in the following manner:

a. Sound vibrations in the air hit against the tympanic membrane, causing it to vibrate.

b. This vibration affects the slender point just beneath the membrane, causing the stimulus to be transferred to the nerve fibers.

Directional sensitivity to sound is exhibited by the locust which turns to face the source of a sound and extends its forelegs on which are located the tympanic organs.

The tympanic organs in beetles and flies are sensitive to low-frequency vibrations, but in other insects these organs respond to sounds of higher frequencies. Sensory hairs, called sensilla, widely distributed on the surface of caterpillars and on the cerci of crickets, cockroaches, and grasshoppers are sensitive to low frequency sounds.

The tympanum in the moth is so sensitive that moths are able to detect the high frequency sounds emitted by approaching bats which prey on them. Recordings from the tympanic nerves show that the moths detect bats at a distance much greater than that at which they show behavioral escape reactions; this distance can be as great as 5 to 6 miles on occasion. Researchers have found that by attaching electrodes to the nerve leading from the moth's ear, sounds emitted by bats can be readily detected.

MAGNITUDE:

Frequency discrimination appears to be poor in insects, as is evidenced by lack of synchronization of nerve impulses with sound and by behavior tests with pure tones. The insect threshold for moderate frequency sounds is high. Apparently, insect ears are not adapted for the frequency discrimination and harmonic analysis which are so important in mammals.

The nerve discharge in insects often shows bursts of impulses at the modulation frequency of a modulated sound and relatively independent of the carrier frequency.

Insects appear to distinguish sounds by modulation frequency or repeated patterning of pulses; this is a temporal pattern of sound units rather than wave form and phase. In all experimental tests, pulsed sounds seem to be detected better than pure tones.

The sensitivity of tympanic organs has been determined by recording the action potentials in the sensory nerves and by noting the behavioral responses to sounds. Tympanic organs are relatively insensitive to low frequencies, but at 10,000 cps and above, the sensitivity approaches, and in some cases exceeds, that of the human ear. Katydids exhibited responses from 800 to above 45,000 cps. Crickets range from 300 to 800 cps.

In the locust, electrical responses recorded from the tympanic organ show that sensitivity increases to a peak at 1,000 decreases, and then rises again to 90 kc. The

threshold at frequencies about 10 kc may approach 0.04 dyne/cm, which is lower than that of the human ear at this frequency.

In the grasshopper, Paroya, the nerve impulses are synchronous with sound frequencies below 200 cps and asynchronous from 450 to 10,000 cps.

For Johnston's sound receptor organ, the frequency range of sensitivity goes from 400 to 525 cps in young male mosquitoes and from 250 to 700 cps in older ones.

In the noctuid moth, the 2 scolopes (sense cells) contained in the sensillae respond to sound over the range of 3 to 240 kc but are most sensitive at 15 to 60 kc. The nerve fiber response is asynchronous, which means it does not correspond to the sound frequency. However, single fibers may fire at 1,000/sec and this response adapts rapidly. The scape moth, Ctenucha, responds to sound frequencies from 150 to 14,000 cps, and at high intensities to yet higher frequencies as long as its tympanic organs are intact.

The chordotonal organs, which occur without tympanic membranes in the tibiae of Orthoptera, Blattaria, Lepidoptera, and a few Hymenoptera, are able to detect substrate vibrations up to 8,000 cps.

The subgenual organ on the leg of Locusta and Decticus responds to vibrations of the substrate with maximum sensitivity at 1,500 to 2,000 cps. The threshold at this frequency is a 3.6×10^{-9} cm movement.

SIMILAR EXAMPLES:

The organs of hearing in other animals also have both a tympanic membrane which serves to couple the sound to the transducer cells and sensory hairs which respond to or transduce sound waves to provide nerve impulses.

SAMPLE PHYSICAL ANALOGS:

The organs of sound reception in insects can be said to consist of parameterization and transduction elements. The relative simplicity of some insect sound receptors compared to those of mammals leads us toward the conclusion that the parameterization may not be complete, i.e., that many different types of sound patterns distinguished by mammals would all be received equally by insects. In the case of Johnston's sound receptor organ, the parameterization is essentially narrow bandpass filtering to select sounds in a limited frequency range.

The filamentary cells that provide a sound detection capability apparently respond to a very wide range of frequencies. While no precise analog of this type of sensor exists, it would appear to be worthwhile to investigate fairly precise structural models of these sensors. The potential gains are: (a) miniaturization of sound detectors; (b) increased dynamic range of sound detectors.

REFERENCES: 34, p. 24; 55, pp. 416-419; 116, pp. 311-314
120, pp. 127-157.

Physical Class	Physical Operator	Section 15
Acoustics Electricity and Magnetism Fluid Mechanics	Sensors Contact Distance Internal	Sound Sensitivity

SOUND SENSITIVITY IN FISH

DESCRIPTION:

Fish, in general, lack the various accessory devices by which sound waves reach the internal ear in higher vertebrates. But, as shown by studies on men with hearing deficiencies, the conduction of vibration through the skull to the internal ear produces some degree of hearing. Water vibrations, to be heard by most fish, must set up head vibration, and these in turn produce endolymphatic vibrations which are picked up by the hair cells of the internal ear.

There is no positive evidence as to the location in the endolymph of the sensory receptors in fish for hearing vibrations. A considerable amount of evidence has been offered indicating that hearing is present in many forms.

ILLUSTRATION:

Some bony fish, such as the Ostariophysi, have accessory structures which parallel the "hearing aids" found in land vertebrates. In these fish, the swim bladder is utilized as a device for the reception of vibrations. In herring-like teleosts this air bladder sends forward a tubular extension which lies alongside part of the membrane system of either ear and can thus induce endolymph vibrations.

MAGNITUDE:

Bony fish have been extensively studied by conditioned reflex techniques with respect to hearing threshold, range, and pitch discrimination. For instance, the catfish Ameiurus has a constant threshold from 60 to 1600 cps; above this range the threshold rises sharply, with conditioned responses obtained at frequencies as high as 13,000 cps.

SIMILAR EXAMPLES:

The sound receptors for airborne sound, found in insects, have a graded polarization and depolarization of the sound sensing membrane, as have many fish.

SAMPLE PHYSICAL ANALOGS:

The air bladder in fish serves as a resonator and as a means for coupling water vibrations to sound receptors. For analogs of other aspects of hearing, see other entries in this section.

SOUND SENSITIVITY IN FISH, Continued:

REFERENCES: 110, pp. 357-374; 121, pp. 518-520.

Physical Class	Physical Operator	Section 15
Acoustics Electricity and Magnetism	Sensors Transformers Distance Energy	Sound Sensitivity

THE TONE COMBINATION EFFECT

DESCRIPTION:

When two tones are sounded simultaneously, other tones, called combinational tones, can usually be heard by persons with normal hearing. Combinational tones are of two kinds, differential tones and summational tones. The differential tones have a pitch equal to the difference of the frequencies of the two sounded tones, and the summational tones have a pitch equal to the sum of the frequencies of the two sounded tones.

Combinational tones originate from nonlinearities in either the ear or the musical instrument producing the tones. For example, if the sound source consists of two tuning forks, combinational tones are produced within the ear alone. If sound is produced by the harmonium, the combinational tones are generated in the air contained within the instrument and can be amplified by tuned resonators.

On investigating the combinational tones of two compound musical tones, it was found that both the primary and the upper partial tones may give rise to both differential and summational tones. In such cases the number of combinational tones is very great. However, the differential tones are stronger than the summational tones, and the stronger generating simple tones also produce the stronger combinational tones. The combinational tones, indeed, increase in a much greater ratio than the generating tones, and diminish also more rapidly. In musical compound tones the prime generally predominates over the partials, the differential tones of the two primes are generally heard more loudly than all the rest. They are most easily heard when the two generating tones are less than an octave apart, because in that case the differential is deeper than either of the two generating tones.

ILLUSTRATION:

When the tones g'''' (at 3168 vibrations/sec) and f''''# (at approximately 2970 vibrations/sec) are sounded together on fifes or on a concertina, the difference tone, g, at 198 vibrations/sec can usually be heard. Although high notes forming semitones produce the loudest combinational tones, difference tones can be readily distinguished when tones forming an interval of a third, fourth, or fifth are sounded on two recorders (blockflutes).

MAGNITUDE:

As the name implies, a difference tone has a pitch determined by the difference between the frequencies of two other tones; a summation tone's pitch results from the addition of

THE TONE COMBINATION EFFECT, Continued:

frequencies. Thus the first difference tone D_1 has a pitch number coming from the substraction of one frequency from the other; e.g., if the higher tone (h) has a frequency of 1000 cps and the lower one (l) is 700 cps, D_1 = h-l = 300 cps. The first summation tone S_1 would come from the summing of the fundamentals; S_1 = h+l = 1700 cps. There are two "second-order" difference tones: 2h-l and h-2l; three of the third order: 3h-l, 2h-2l, 3l-h; four of the fourth order: 4h-l, 3h-2l, 2h-3l, 4l-h; etc. In general, the pitch number for any particular combination tone (difference or summation) is given by the expression: N=mh±nl; m and n are any integers satisfying the condition, m+n-1= Orders, for any given order.

Obviously a very large number of combination tones is obtainable, though from direct observation few appear. The reason is that combination tones lying at or near the location of either of the fundamentals or any of the prominent overtones of either fundamental may be masked to the point of inaudibility. Strong fundamentals are necessary to produce the distortion pattern to which the combination tones owe their existence; this situation also produces powerful masking. Analysis of the electrical potentials in the guinea pig's cochlea, under strong stimulation by tones of 700 cps and 1200 cps has, however, revealed the existence of 64 combination tones simultaneously present.

SIMILAR EXAMPLES:

The phenomenon of masking is similar to the combination tone effect. If two tones of different frequency, one high and the other of low intensity, are simultaneously led to the same ear it is likely that the weaker one will not be heard at all. It is said to be "masked" by the stronger.

SAMPLE PHYSICAL ANALOGS:

Since the difference tone arises from nonlinearities in either the sound detection or transmission equipment, modulation and demodulation equipment produce analogs of this effect. In the superheterodyne receiver, the difference frequency between an incoming high-frequency signal and a locally generated signal slightly higher in frequency than the incoming signal are mixed to produce an intermediate frequency signal (at the difference frequency). The intermediate frequency signal is then amplified prior to final detection. It should be noted that both sum and difference frequencies appear in all modulation or mixing operations, but the sum frequency is filtered out in the superheterodyne receiver.

REFERENCES: 37, pp. 128-133; 59, pp. 5, 152-154.

SECTION 16:

TACTILE SENSITIVITY

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BIOLOGICAL ASPECTS OF TACTILE SENSITIVITY

Tactile sensitivity is a function of the force per unit area on the skin surface. On the hairy regions of the skin of man, response to touch depends on nerve fibers wrapped around the base of hairs; these act as levers to increase the effect of small movements near the skin surface in distorting the ends of the fibers. The sensitivity of such organs reaches its extreme development in the vibrassae of many mammals. These may be sufficiently sensitive to respond to small air movements and thus become distance receptors like the eye, the nose, or the ear.

Another aspect of touch sensitivity is the power to distinguish patterns and qualities of incident movement. A distribution of receptors sufficiently dense to allow discrimination between patterns differing in fine details occurs in some areas of the skin of primates, such as the fingers, where there are special organized nerve endings consisting of a few epidermal cells, associated with the nerve fibers.

The nerve fibers in the skin pass through an elaborate plexus; this arrangement of fibers is presumably of primary importance in determining the pattern of impulses projected centrally from the stimulation of a given group of receptors in the skin.

PHYSICAL ANALOGS IN GENERAL

From a physical point of view, tactile sensitivity can be thought of as a combination of force (or possibly pressure) and vibration detection, or, even more generally, as vibration detection if displacement is treated as the zero level mode of vibration. The tactile sense involves more than a single point sensor, of course; it also involves spatially distributed sensors which provide the characteristics of textures.

Physical devices that provide electrical signals in response to deformation or vibration include piezoelectric crystals, electromagnetic pickups for phonographs, accelerometers, microphones, and strain gages. These are usually based upon either piezoelectric effects or some type of electromagnetic principle. The seismograph provides a visible record of vibrations but does not necessarily provide electrical outputs, since purely mechanical devices can be used to detect and record vibrations.

Physical Class	Physical Operator	Section 16
Aerodynamics Mechanics	Sensors Contact	Tactile Sensitivity

AIR CURRENT SENSORS

DESCRIPTION:

Air current sensors, also called anemoreceptors, enable organisms to orient themselves in relation to the direction and speed of the air current (anemotaxis). Although these sensors are not described in the literature as specific anatomical entities there are numerous examples of anemotaxis, especially among the invertebrates. A critical evaluation of these examples leads to the fairly reasonable conclusion that these sensors are closely connected to the sense of touch.

ILLUSTRATION:

a. Among the invertebrates, the halteres of flies have been shown to be sensors that are stimulated by air currents. These structures, which take the place of the posterior pair of wings in the Diptera, enable poising insects of this kind to orient themselves into the wind. See "Balance and Flight of Insects".

b. Among the vertebrates, migrating birds are known to direct their flight into the wind, while communal birds, such as gulls and ducks, all come to rest facing in the direction of major air currents. During the recent investigations of the perception of visual information by tactile stimuli in humans, very small jets of air were used to stimulate the subject's skin. The results indicated that the phenomena of apparent location and apparent motion could both be produced by air jet stimulation. The apparent location, for instance, was produced by simultaneous stimulation with air jets of different pressure intensities.

SIMILAR EXAMPLES:

See "Rheotaxis", "Geotropism" and "Thigmotaxis".

SAMPLE PHYSICAL ANALOGS:

The Q-ball, an instrument for determining the angle of approach (or attack) in air, is an analog of the anemoreceptor organs.

REFERENCES: 33, pp. 256-260; 36, p. 29; 116, p. 293; 144, p. 768.

Physical Class	Physical Operator	Section
Mechanics	Sensors Contact Actuators External	Tactile Sensitivity

BABINSKI REFLEX EFFECT

DESCRIPTION:

The Babinski reflex is elicited by stroking the outer margin of the sole of the foot from the heel to the small toe. The resulting reaction has two phases: an initial digital extension particularly the big toe, and a subsequent lateral fanning.

ILLUSTRATION:

In the human infant, stimulation of the sole of the foot results in a lateral extension of the toe. During maturation, the reflex changes to a flexion of the toes inward. In adults moreover, the appearance of a positive (extension) Babinski reflex is an abnormal condition which may indicate damage or deterioration of the pyramidal tract of the central nervous system.

Similar reactions are obtained with the chimpanzee, the baboon and the gibbon.

MAGNITUDE:

The Babinski reflex persists indefinitely in the chimpanzee. In the baboon, removal of the cortical motor area associated with the leg produces the response, and motor recovery is slow. In the gibbon, believed to show even higher cortical dominance, the Babinski reflex is well developed for 3 weeks after removal of the cortical motor area, and return of motor functions is even more slow than exhibited in the baboon.

SIMILAR EXAMPLES:

Scratching the skin of the buttock causes contraction of the gluteal muscles. It depends upon the integrity of the 4th and 5th lumbar and upper sacral segments. Light scratching of the skin on the abdomen of a normal person causes a reflex contraction of the abdominal muscles.

Oppenheim's reflex consists of dorsiflexion of the hallux which results when a firm downward sliding pressure is applied to the skin over the anterior border of the tibia.

SAMPLE PHYSICAL ANALOGS:

Reflexes, in general, are crudely modeled by trigger circuits which provide a fairly uniform impulsive response to a triggering input. Modifications in reflex responses have their analogs in wave shaping circuits whose characteristics can be modified.

REFERENCES: 7, pp. 1205, 1211, 1212; 31, pp. 807-808; 68, p. 1041; 122, p. 197.

Physical Class	Physical Operator	Section 16
Fluid Mechanics Mechanics	Sensors Transformers Distance Information	Tactile Sensitivity

LATERAL LINE ORGANS

DESCRIPTION:

Lateral line organs are found in all fish and in many of the early Amphibia. They consist of a complex system of sensory canals containing fluid or mucus. They run along the sides of the body and often on the head, either covered,with a few openings, or entirely open and exposed. At one time they were arranged in 3 parallel rows down each side of the body. However, the middle row is the only remaining one in most fish.

The walls of these canals have epithelial cells and specialized hair cells called neuromasts which are frequently grouped together as sensory ridges, with their hair processes projecting into a gelatinous "capula". The openings exposing the lateral line organs in fish are either between the scales or are pores which penetrate the scales.

ILLUSTRATION:

The lateral line system is directly concerned with the sense of touch at distances in sensing ripples and vibrations, localizing moving objects such as other aquatic animals, and detecting fixed objects by reflecting waves.

Movement of an object in the water in the vicinity of a fish with active lateral line organs originates currents. These currents move the fluid in the tube-like canals of the lateral line organs, causing the sensory hair-like neuromasts in the canal to stimulate the branched fibers of the lateral line nerve, thereby signalling the fish.

It has also been suggested that the canals record displacements produced by the fish while swimming.

MAGNITUDE:

The nerve fibers show a continuous background of spontaneous activity which originates in the neuromasts. This system responds to vibration frequencies from about 100/sec in most fish up to about 500 vibrations/sec in some. Modulation of these nerve fibers is obtained by mechanical stimulation of spontaneously active neuromasts and is measured in cycles of low-frequency wave stimulation. This varies in different species from several spikes per cycle (< 20/sec) up to 100/sec.

SIMILAR EXAMPLES:

The scattered pit organs are independent groups of receptor cells distributed mostly on the head of a fish. They may be isolated from each other or regularly arranged either in rows at the bottom of the grooves or in canals which open at intervals to the outside by means of pores.

LATERAL LINE ORGANS, Continued:

In elasmobranch fish the Ampulli of Lorenzini are highly modified pit organs which are temperature receptors. They are deeply imbedded below the surface and enlarged into a bulb-like cavity at the bottom of an elongated duct that becomes completely sealed off from the outside. Both the bulb-like cavity and the duct are supplied with receptor cells, surrounded by abundant mucus and terminating with sensory hairs.

The Vesicles of Savi, found only in the aberrant electric fish, Torpedo nobiliana, are located along the outer edges of the electric organ on either side and around the border of the nasal pits.

Investigators in Herefordshire, England, discovered a large number of fossilized specimens of the prehistoric fish, Cephalaspis and Pteraspis. Examination of the dorsal surface of one of these fossil skulls revealed a number of small depressions each covered by a small scale and having wide canals leading to the vestibular region. Two theories were postulated concerning the possible function of these canals. The first was that they could have contained nerves. The second and more plausible theory, based on present day knowledge of similar structures, was that they may have contained tubular extensions of the labyrinth, thereby transmitting pressure waves to the ear. In this manner, these canals may have functioned as substitute reinforcements for a defective lateral line system.

SAMPLE PHYSICAL ANALOGS:

The functions of lateral line organs range from flow metering to vibration detection and have corresponding devices as analogs.

The signals from lateral line organs are used in object detection (and, possibly, ranging) for which a sonar system is analogous.

REFERENCES: 33, pp. 250-253, 260; 64, pp. 77, 82, 695-714; 73, pp. 87-99; 75, pp. 776-777; 116, pp. 294-295; 153, pp. 127, 218-220.

Physical Class	Physical Operator	Section 16
Mechanics	Sensors Contact Transformers Information	Tactile Sensitivity

MEISSNER'S CORPUSCLES

DESCRIPTION:

Meissner's corpuscles are encapsulated endings found in the papillae of hairless skin regions. They consist of a spiral arrangement of nerve fibers that branch and end in knots. They are believed to be the tactile receptors in primates.

ILLUSTRATION:

It has been hypothesized that free nerve endings are the receptors for pressure on hairy regions of the body and that the Meissner's corpuscles were effective in hairless areas. The main argument for this is based on the matter of distribution. The lips and parts of the hands and feet are highly responsive to pressure and the Meissner's corpuscles are plentiful in these areas.

The nerve fibers leading to the corpuscles approach the cluster from various directions indicating that there may be considerable overlap from several fibers.

MAGNITUDE:

Meissner's corpuscles occur in hairless skin regions in groups of 2 or 3, and 10 such groups may occur in an area of about 1 mm^2. Contacts on, for instance, the finger tips of one or a few millimeters apart can be recognized as distinct. On the hairy portions of the skin, the minimum distance at which points can be discriminated increases to about 1 cm.

SIMILAR EXAMPLES:

Thermal receptors similar to tactile receptors have been postulated. The Krause end bulb is the receptor for cold. This has been partially verified anatomically in that areas of the surface of the eye most sensitive to cold showed the greatest concentration of Krause end bulbs. The Ruffini cylinder is reported to be the end organ for warmth.

Pacinian corpuscles respond to rate of mechanical deformation. See also "The Touch Sensation".

SAMPLE PHYSICAL ANALOGS:

Since Meissner's corpuscles apparently respond to deformation or to pressure by triggering nerve cells, pressure transducers or indicators, such as the sphygmomanometer (which is used to measure blood pressure) are analogous.

REFERENCES: 37, pp. 170, 190-192, 225; 152, p. 477.

Physical Class	Physical Operator	Section 16
Chemistry Electricity and Magnetism Heat and Thermodynamics Mechanics	Sensors Contact Internal Transformers Information	Tactile Sensitivity

PAIN DETECTION

DESCRIPTION:

The sensory receptors for pain are spread throughout the body and three general types of pain can be recognized: superficial or cutaneous pain; deep pains from muscles, tendons, joints, and fascia; and visceral pain. Pain can be elicited by several kinds of stimulation, electrical, mechanical, thermal and chemical. This indicates that the receptors are not necessarily specialized to any particular kind of stimulation as may be the case with other cutaneous receptors.

ILLUSTRATION:

Much evidence points to the free nerve endings as the receptors for pain. The cornea of the eye presented the most definitive support for this theory in that it contains only free nerve endings and was thought to be sensitive only to pain. However, recent investigation has refuted this fact. Under carefully controlled conditions, a group of investigators applied brass cylinders, similar to the type used in thermal exploration of the skin, to the cornea. The resulting sensation was one of pressure rather than pain.

The phenomenon of double pain provides additional information on pain signal conduction. Observers have reported a sharp sudden pain at first, followed by a longer lasting second pain, the first a pricking sensation and the second, a burning ache. The temporal separation between the two has been attributed to a difference in the rates of conduction of two types of nerve fibers; the faster pain is conducted by medullated fibers and the slower by unmyelinated ones.

MAGNITUDE:

Pain conduction in medullated fibers proceeds at the rate of 14.45 m/sec whereas unmyelinated fibers conduct at approximately 2 m/sec.

For a standard 3 sec exposure, the absolute threshold for pricking pain is 220 millicalories. The practical upper limit is about 480 millicalories.

Investigations on the cat's tactile sensitivities have shown that pain impulses travel along the nerves at less than 5 m/sec as compared to 30 to 60 m/sec for impulses received from the cat's sensory hairs.

By the careful mapping of certain cutaneous regions a normal human adult has been shown to have in his skin the following approximate receptor ratios, which indicates that pain receptors are far more numerous than other tactile receptors.

PAIN DETECTION, Continued:

Estimated No.		Ratio
30,000	Caloreceptors	2
250,000	Frigidoreceptors	13
500,000	Tangoreceptors	25
4,000,000	Algesireceptors (Pain)	200

SIMILAR EXAMPLES:

Itching seems to result from rather minimal stimulation of the free nerve endings. It is also brought about as an after effect of the sharp sensation of pain. It can be induced by electrical, chemical or mechanical stimulation.

SAMPLE PHYSICAL ANALOGS:

Since pain receptors are indicative of a condition of bodily overstress, any transducer providing out-of-tolerance signals is analogous to a pain receptor.

REFERENCES: 30, p. 498; 37, pp. 197, 202-204, 208; 123, pp. 311-313, 326-327.

Physical Class	Physical Operator	Section 16
Mechanics	Sensors Contact Transformers Information	Tactile Sensitivity

PRESSURE DETERMINATION

DESCRIPTION:

The sensation of pressure results from tension within the cutaneous tissue. The receptors are believed to be the free nerve endings around hair follicles in the hairy regions of the body and Meissner's corpuscles where there is no hair. This theory is based primarily on the wide distribution of these receptors throughout the body.

ILLUSTRATION:

Adaptation can occur with pressure sensation as it does with other sensory processes. The rate of adaptation may depend on several variables: location on the body, size of the area stimulated, and the intensity of the stimulus. The more intense the stimulus and the smaller the cutaneous area, the faster adaptation will occur.

Experimental observation has shown that if a given stimulus is applied over a period of time, it will continually move downward on the skin for a long while. The pressure sensation continues as long as a supraliminal rate of movement is maintained. The obvious conclusion would be that adaptation results from stimulus failure, the stimulus causing tension of the cutaneous tissue.

Similarly, when the stimulus is removed a new pressure sensation should occur, since again there is a readjustment of tension in the skin. This readjustment seems to correlate with the so-called "aftersensation" of pressure.

MAGNITUDE:

Pressure thresholds are reached at an approximately constant level around 0.85 g/mm^2. A minimal energy of 0.4 erg, when applied to the end of a hair which is 1.0 cm long, will exceed the sensation threshold.

A direct comparison of this sense with visual or auditory phenomena shows that the skin absorbs from 100 million to 10 billion times the energy required for minimal activation of the eye or the ear.

SIMILAR EXAMPLES:

In much the same way that itching is a derivative of the pain sensation, so tickling and vibration are related to the pressure sensation.

Tickling will result for the gentle movement of a hair or a light brushing of the hairless regions as the lips. The threshold for a vibratory sensation varies directly as the pressure threshold does for any particular receptor locations,

PRESSURE DETERMINATION, Continued:

thereby strongly suggesting that the same receptors are involved in both processes.

SAMPLE PHYSICAL ANALOGS:
See the analogs in the entry, "Meissner's Corpuscles".

REFERENCES: 37, pp. 179-189.

Physical Class	Physical Operator	Section 16
Fluid Mechanics	Sensors Contact	Tactile Sensitivity

RHEOTAXIS

DESCRIPTION:

Rheotaxis is the change in the orientation of an organism in response to mechanical stimulation by a current or stream of water. This type of reaction is very common among animals; it may occur in planarians, gastropods, crustaceans and fish as well as in the nymphs, larvae and imagoes of insects.

ILLUSTRATION:

In fish, rheotaxis depends, in a very broad sense, on three sensitivities. As long as the fish can see, it will rely on optical ability to fix its surroundings. In a smooth channel, if the fish is already impeded by friction, it will make use of the lateral line organs; however, true rheotaxis occurs when the fish is in contact with a medium (such as the ground or a liquid stream) and the mechanical stimuli are primary.

When the minnow, Phoxinus laeris, was blinded experimentally, it could not orientate unless some mechanical stimulation and contact with a solid object was provided.

The Planaria alpina will put out a layer of mucus and move over it in a pedal wave fashion. This is interposed like a cushion between the ground and the animal's contact receptors. In this case, then, the receptors responsible for rheotaxis are current receptors, i.e., the sensors are sensitive to motion of the liquid relative to the animal.

In the invertebrates, the process is always determined by optic fixation.

MAGNITUDE:

Planaria alpina are positively rheotactic when the temperature is over 12°C; that is, they will migrate upstream. If the temperature is below 12°C, sexual maturity will likewise result in migration upstream until breeding takes place. The overpopulation then leads to relative starvation which in turn, in temperature below 12°C, will result in negative rheotaxis or migration downstream.

SIMILAR EXAMPLES:

The orientation to air currents, or anemotaxis, in flying animals is similar to the rheotaxis phenomenon. In flies, for example, antennal sense organs are sensitive to wind and therefore will elicit postural changes in accordance with the speed of air flow. See also "Thigmotaxis", "Geotropism", and "Air Current Sensors".

RHEOTAXIS, Continued:

SAMPLE PHYSICAL ANALOGS:

Rheotaxis depends upon several sensors and upon the nervous system which acts as a control system. For analogs of controllers see Section 5, "Equilibrium Sensing and Control".

REFERENCES: 33, pp. 250-256; 116, p. 293.

Physical Class	Physical Operator	Section 16
Mechanics	Sensors Contact Transformers Information	Tactile Sensitivity

TACTILE ORGANS

DESCRIPTION AND ILLUSTRATION:

Many of the lower forms of animals have large numbers of small tactile hairs distributed over the surfaces of their bodies. Similar sensory hairs are found in higher animals as well. An insect such as the fly is covered with sensory bristles. In nocturnal mammals, such as mice or cats, these tactile hairs are used to determine the presence of obstacles in the dark.

The coelenterates show the first true tactile organ, the tentacle. The tentacles are arranged in a circular fashion around the mouth in the polyp and the jellyfish. The organs contract when stimulated mechanically. The same type of reaction is obtained by stimulating the fleshy tentacles on the head of a marine Nereid worm. In insects such as the katydid, these organs may extend the entire length of the body.

Tentacle-like organs may also be found in vertebrates, for example, the catfish.

MAGNITUDE:

In hydra, the tentacles are capable of extreme expansion, stretching out from a small blunt projection to a thin thread 7 cm or more in length. The number of tentacles may vary considerably. Six hundred specimens of Hydra viridissima displayed from 4 to 12 tentacles each; 54% had 8; 24%, 7; 15%, 9, and only a few in the other categories. The number of tentacles may increase with the size and age of the animal.

SIMILAR EXAMPLES:

Reactions to gravity are closely related to the tactile senses. Jellyfish possess a small organ at the base of the tentacles called a lithocyst. It contains a freely moving granule which falls on the sensory hairs around it, indicating the downward direction. All sense organs reacting to gravity appear to have these sensory hairs.

In the semicircular canal of vertebrates, the sensory hairs detect the fluid indicating a change in position.

SAMPLE PHYSICAL ANALOGS:

Tactile organs in animals are used in many different ways, and physical analogs vary accordingly. For example, "curb feelers" on automobiles provide an audible signal when in moving contact with a solid surface and are analogous to the tactile hairs of nocturnal animals in detecting solid objects.

TACTILE ORGANS, Continued:

REFERENCES: 58, p. 144; 132, pp. 40-41.

Physical Class	Physical Operator	Section 16
Mechanics	Sensors Contact	Tactile Sensitivity

THIGMOTAXIS

DESCRIPTION:

Thigmotaxis is the instinctive preference of certain insects such as bedbugs, cockroaches and scorpions for narrow tight crevices in which their bodies are in close contact with the surrounding surfaces. This characteristic behavior is also called thigmotropism or stereotropism although the latter generally refers to botanical phenomena.

ILLUSTRATION:

This particular reaction differs from other kinesthetic motion in that the animal is not under the influence of the stimulus until it actually finds the crevice and remains there.

When the animal reaches the crevice, it presses its body against the available surfaces. For example, the earwig, Forficula, presses its body against the wall of a dish so that it curves to fit the wall.

When the salamander, Triturus torosus, is stroked along the side of the body, it rolls over so that the dorsal side can also be stimulated. Similarly, if the tail is stroked, it will bend around to the stimulated side, thereby increasing the amount of contact with the surrounding surface. This type of behavior will occur reliably in the decapitated animal or even the isolated tail.

MAGNITUDE:

The intensity of the stimulus is often critical. If, for example, a phototactic animal (one orienting towards light) is placed between two light sources which vary in intensity, it will usually orient toward the one which is nearer the "sensitivity threshold" for the particular species.

SIMILAR EXAMPLES:

Some similar types of behavior involve a measure of learning. For example, menotaxis, whereby an animal moves at a fixed angle to a source of light, may involve a small degree of learning. The homing insect learns the proper angle for his return trip during his journey outward. The dorsal light reaction of fish and insects is a special case of menotaxis in that the animals constantly maintain their longitudinal axis at right angles to the light source.

See also "Geotropism", "Rheotaxis", and "Air Current Sensors".

SAMPLE PHYSICAL ANALOGS:

Since thigmotaxis involves not only tactile sensors but

THIGMOTAXIS, Continued:

also a behavior pattern following stimulus of the sensors, a complete control system is required to model thigmotaxis. Such a system would contain sensors, a controller and a set of actuators.

REFERENCES: 33, pp. 248-249; 45, pp. 991-992; 102, p. 505; 120, pp. 703-706.

Physical Class	Physical Operator	Section 16
Mechanics	Sensors Contact Transformers Information	Tactile Sensitivity

THE TOUCH SENSATION

DESCRIPTION:

Meissner's corpuscles and Merkel's discs are believed to be the receptors for the touch sensation. They are composed of the dendrites of sensory neurons which are enclosed in capsules of varying complexities. This increases the amount of area which is exposed to contact since these encapsulations are close to the skin. Merkel's discs contain flattened plates which constitute the specialized nerve endings. Their sensitivity to manipulation is the critical characteristic which identifies them as probable touch receptors.

Pacinian corpuscles, which are numerous in the palm of the hand and the sole of the foot, respond to rate of mechanical deformation and also contribute to the sensations resulting from tactile stimuli. (See also "Tactile Organs.")

ILLUSTRATION:

Similar to pressure, touch is aroused by a mechanical deformation of the skin. This is concluded from the observation that, when a finger is submerged in mercury, sensation is felt only at the surface between the mercury and the air where deformation occurs, rather than throughout the entire finger.

There seems to be a reciprocal relation between the presence of hair in mammals and specific tactile receptors. Similarly, in birds, these receptors occur mostly in the regions having no feathers.

MAGNITUDE:

The size of the receptor unit varies in different species and on different parts of the body. The area of one unit in the cat's tongue is 5 mm^2 whereas in the skin of the frog, it is 100 mm^2.

In man, the end organs of the encapsulated receptors found in the subcutaneous tissue and also in deeper tissue may be excited by deformation of 0.5mm applied for a period of 100 ms.

The results of the quantitative experiments described by Burton-Opitz are given in the following table, which gives the distance along the surface of the skin at which two points of calipers can be felt as two rather than one (two-point discrimination).

THE TOUCH SENSATION, Continued:

		mm
a.	Palm of the last phalanx of finger	2.2
b.	Palm of the second phalanx of finger	4.4
c.	Tip of the nose	6.6
d.	Back of the second phalanx	11.1
e.	Back of hand	29.8
f.	Forearm	39.6
g.	Sternum	44.0
h.	Middle of back	67.0

SIMILAR EXAMPLES:

The sensations of touch and pressure are very similar; some investigators believe that the latter results simply from a more intense stimulation of the same receptors as the former.

One of the main differences is due to the fact that a wider area of skin is stimulated to achieve pressure; furthermore, the sensation of touch is more definitely localized in time and space than is pressure.

SAMPLE PHYSICAL ANALOGS:

See the analogs in the entry on "Meissner's Corpuscles".

REFERENCES: 68, pp. 876-878; 144, pp. 755-756, 760.

Physical Class	Physical Operator	Section 16
Fluid Mechanics Mechanics	Sensors Contact Distance	Tactile Sensitivity

VIBRATION RECEPTORS IN THE SPIDER

DESCRIPTION:

Arthropods are highly sensitive to vibrations of the substratum, which may be either solid or liquid. They also have been found to respond to airborne sounds. The vibration receptors are most frequently short sensory hairs, called sensilla, attached to the chitinous covering at the joints of the insects. The sensilla of the common house spider, Achaearanea, are found under its thin chitin near the tarsal-metatarsal joints of its legs.

ILLUSTRATION:

A spider walking across its web varies the amount of stress being placed on its tarsal sensillae and thus is able to change the frequency of maximum sensitivity of these vibration sensors. The spider detects an insect caught in its web by vibration.

MAGNITUDE:

Under certain conditions, the spider sensilla can detect vibrations in a higher frequency range than some of the more characteristic animal phonoreceptors. Since these sensory hairs are somewhat tuned by their own resonant frequency, they are able to differentiate between frequencies in the range of 100 to 1,000 cps. Spiders have been shown to respond to vibrations of 2,000 cps, the amplitude of which was 25 Å. When an inanimate vibration source of 400-700 cps is placed on the web, the spider will attack immediately.

SIMILAR EXAMPLES:

At the lower frequency limits, vibration receptors are quite similar to tactile sensors and proprioceptors, while at the higher limits they resemble sound receptors.

SAMPLE PHYSICAL ANALOGS:

Electromechanical vibration sensors are used in testing vibratory properties and for analyzing equipment in vibration stress tests. Two types of vibration sensors in common use are crystal detectors that make use of piezoelectric effects and electromagnetic devices that use variable reluctance or generator principles.

REFERENCES: 116, pp. 295-296.

SECTION 17:

THERMAL SENSITIVITY

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BIOLOGICAL ASPECTS OF THERMAL SENSITIVITY

Thermal sensitivity limits the distribution of animals and regulates their activity. In general, life activities occur only within the range of about 0°C to 40°C although most animals live within much narrower limits; some survive but are inactive below 0°C.

The maintenance of a certain temperature is of vital importance to the organism because all biologic processes are conditioned by temperature. In mammals the central nervous system ceases to function at 44 to 45°C and the heart stops beating at 48°C. A rise in temperature of 5°C causes a twofold to threefold increase in pulse rate, oxygen consumption, etc.

The mechanisms of heat regulation are activated in two ways: by thermal receptors in the skin, and by direct stimulation of the thermoregulator in the brain by changes in blood temperature.

Heat and cold receptors are distributed in a definite pattern in the skin, the warmth receptors are usually deeper than the cold receptors although the latter are the more numerous. Some thermoreceptors may be encapsulated but many are free nerve endings. Much sensory summation occurs so that the threshold for stimulation decreases as the size of the area stimulated increases. Sensations occur for changes in temperature of a few thousandths of a degree in a second.

The influence of temperature on the activity of insects is illustrated as follows: The noctuid moths will flap their wings frequently at great speeds prior to flying. This preflight activity was attributed to a necessity for "warming up" the flight muscles to the proper temperature. This is quite similar to the "warm-up" period necessary in a propeller-driven airplane. Experimentation with caged moths kept at different temperatures and then released led to the finding that at 86°F, the moths required no preflight period but were able to start flying immediately from a stationary position.

PHYSICAL ANALOGS IN GENERAL

The effects of temperature on living creatures become directly evident in poikilothermic (cold-blooded) animals as a result of metabolic rate dependence on temperature. Metabolic rate changes have been shown to be quite similar to changes in the activity rate of enzymes in relation to temperature and can be

presumed to be a consequence of them. The more complex behavioral changes in poikilotherms are probably a consequence of temperature sensors in these animals. These behavioral changes have no obvious physical analogs.

Homeotherms (warm-blooded animals), however, have a highly developed internal temperature controlling mechanism and, within an optimum temperature range, can adjust to temperature changes by controlling blood flow rate and distribution. Outside this region of "thermoneutrality", other mechanisms come into play in warm-blooded animals to provide adaptation. At low temperatures, the metabolic rate increases to provide extra heat, and at high temperatures sweating and panting provide evaporative cooling. The obvious physical analog of this temperature regulation process in homeotherms is that of a regulatory mechanism consisting of a temperature sensor, a controller, and heating and cooling devices. (See the comments on regulation in the introductory remarks to Section 5, "Equilibrium Sensing and Control".)

The temperature sensors in animals are of two types: one for cold (frigidoreceptors) and one for heat (caloreceptors). There are apparently several kinds of thermal receptors of varying sensitivities in different animals. The most sensitive heat detector thus far reported is the infrared sensor found in the rattlesnake. (For a discussion of this sensor and of the physical analogs for it, see the entry on "Infrared Sensing in Rattlesnakes".) The physical analogs of thermal receptors include thermocouples and thermistors and simple bulb thermometers.

Physical Class	Physical Operator	Section 17
Chemistry Heat and Thermodynamics	Sensors Internal Transformers Energy Matter	Thermal Sensitivity

HIBERNATION

DESCRIPTION:

Hibernation is a period of deep unconsciousness and slowing, almost to arrest, of all the body processes which many animals undergo in the winter months. It is especially common with cold-blooded animals.

ILLUSTRATION:

As winter approaches frogs take to water and burrow into the moist mud at the bottom of ponds below the frost line, where they stay through the winter. While hibernating the frog takes no food, being dependent during this time on the energy stored in its body as fat and glycogen. All activities are suspended except those necessary to maintain life, such as the beating of the heart. Its metabolism is greatly reduced, little oxygen is required, and respiration takes place almost entirely through the skin.

MAGNITUDE:

During hibernation the animal's oxygen consumption may drop from 1/30 to 1/100 of the normal. The heart rate decreases to a few beats per minute and at times there is a complete suspension of breathing for several minutes.

SIMILAR EXAMPLES:

Adjustments to temperature by some animals is by migration or by modifications of structure, such as special seasonal development of fat, fur or feathers. In the Arctic regions, animals such as the Arctic fox, seal, and polar bear are well protected by heavy pelage and thick layers of fat.

SAMPLE PHYSICAL ANALOGS:

There are many chemical processes that are slowed by lowering the temperature. Photographic film is often stored under refrigeration to prolong its shelf life.

REFERENCES: 146, pp. 440-441.

Physical Class	Physical Operator	Section 17
Chemistry Heat and Thermodynamics Optics and Light	Sensors Distance	Thermal Sensitivity

INFRARED SENSING BY RATTLESNAKES

DESCRIPTION:

The rattlesnake has an organ sensitive to infrared radiation. This organ is located in the facial pit between the nares and eye. It enables the snake to strike accurately at prey that produce heat.

The organ consists of a membrane innervated by a superficial branch of the superior maxillary division of the trigeminal nerve and a scalloped inner cavity.

ILLUSTRATION:

The pit functions when the inner cavity is heated by radiation, expanding the air and deflecting the membrane. A small opening near the eye, controlled by a sphincter muscle, communicates with the inner cavity and serves as a safety mechanism when the entrapped gases are subjected to abnormal heat intensity.

MAGNITUDE:

By applying electrodes to the exposed nerve of the sensing organ, it was found that a continuous barrage of impulses was present when apparent stimulation was lacking, but if air movement or temperature changes occurred in the receptor region a change in the level of discharge was reflected by a proportional deflection in the membrane. Stimulus intensity change seldom required more than 150 ms for adaptation. Low sensitivity was registered to wavelengths in the short infrared region (1μ), but greater outputs occurred in the long infrared region, 10-15μ. Even when other sense organs were rendered nonfunctional, the snake still maintained its ability to locate prey and discriminate between it and thermally neutral objects.

SIMILAR EXAMPLES:

Female mosquitoes are attracted to radiant heat, for example, the heat which passes through windows or screens from a warm house at night. Infrared sensitivity is significantly stronger in the female than in the male.

Inasmuch as the snake's infrared sensor is not image-producing, it may be compared with the eyespots of the ant or other small creatures, except that eyespots are normally sensitive in the visual range of the spectrum.

SAMPLE PHYSICAL ANALOGS:

Infrared sensing is an important technique for detecting warm objects such as the plume of a missile during launch. Combined with scanning, or a matrix of sensors, the technique can

INFRARED SENSING BY RATTLESNAKES, Continued:

be used for infrared imaging such as in the case of the World War II snooperscope which could image the figure of a man from his body temperature to provide the capability of "seeing" in the dark. Other applications of IR (infrared) sensing include haze-penetration, signalling, medical electronics techniques wherein the distribution of temperature over the skin of a patient is important, and aerial reconnaissance, where an infrared image, when compared with an image covering the visual spectrum, can provide additional information.

Some IR sensing materials that provide electrical response are photoconducti or photovoltaic materials such as lead sulfide, lead selenide, lead telluride, indium arsenide, thallium sulfide, and zinc-doped germanium. Thermistor material, and infrared photographic film are frequently used where practicable. Many IR sensing arrangements are simply for detecting and are not image-producing.

REFERENCES: 105, pp. 93, 95; 128, pp. 41-47; 135.

Physical Class	Physical Operator	Section 17
Chemistry Electricity and Magnetism	Sensors Contact Internal Transformers Information Actuators Internal	Thermal Sensitivity

MAN'S TEMPERATURE REGULATING CENTER

DESCRIPTION:

The net result of the summed chemical and physical reaction to temperature stress is the regulation of internal temperature constancy despite varying thermal gradients between body and environment. The temperature regulation center that accomplishes this constancy is located in the hypothalamus.

ILLUSTRATION:

Impulses from temperature receptors ascend via lateral spinothalamic tracts and the thalamus to the hypothalamus from which various autonomic reflex responses are activated.

When man's body needs more heat, the hypothalamus sends nerve impulses to the muscles causing contractions and shivering. If the body needs cooling, impulses activate the sweat glands to induce the production of perspiration for evaporative cooling.

MAGNITUDE:

Under basal conditions, man loses about 20% of his heat by vaporization, in exercise 75 to 80%. Loss of heat by radiation exceeds loss by vaporization at low temperatures, but above 31°C loss by vaporization predominates in man at rest.

In cool air, man may lose by evaporation one liter of water per day; in hard work on the desert, he may evaporate 1.5 liters per hour. The temperature regulating center increases the output of sweat 20 grams per hour for each 1° C rise in air temperature.

SIMILAR EXAMPLES:

The temperature regulating centers of many animals are similar to those of man. Local warming of the anterior hypothalamus of a cat produces peripheral vasodilation and increased breathing. Lowering blood temperature, without cooling the skin, will produce shivering. Thus the hypothalamus provides both a temperature regulating center and a second level of detecting mechanism, responding to changes in blood temperature.

SAMPLE PHYSICAL ANALOGS:

The human temperature control system is an example of a human dynamic system approaching the accuracy of an engineered system. Small percentage changes from equilibrium correspond to catastrophes for the total system, e.g., death results from an increase of internal temperature as little as 7° F.

The physical analog for the temperature control system of a man is the dynamic temperature control system of the sun in terms of the scope of activity. By a dynamic interplay of

MAN'S TEMPERATURE REGULATING CENTER, Continued:

nuclear interaction, radiation and gravity, the temperature of the sun is strongly regulated. Small percentage changes in temperature show up as sun spots and could even lead to catastrophe.

REFERENCES: 116, pp. 257-260.

Physical Class	Physical Operator	Section 17
Chemistry Heat and Thermodynamics	Sensors Internal Transformers Energy Information	Thermal Sensitivity

METABOLIC RATE IN POIKILOTHERMS

DESCRIPTION:

The body temperature of poikilothermic (cold-blooded) animals varies with the temperature of their surroundings. All animals, other than mammals and birds, are poikilothermic. Within the temperature range that permits an active and normal life for these animals, temperature change has a profound effect on metabolic processes. Many animals can tolerate temperatures below the active life limit and survive cold in an inactive state. However, their tolerance to increased temperatures is usually quite limited. Within the temperature range that can be tolerated by a poikilothermic animal, the metabolic rate and many other processes are doubled fairly regularly for each temperature rise of 10° C. If the increase continues, the rate accelerates rapidly.

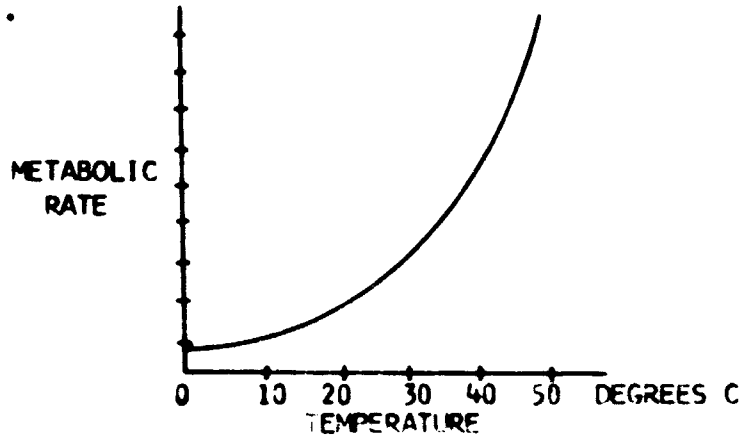

FIG. 25 RELATIONSHIP BETWEEN TEMPERATURE CHANGE AND METABOLIC RATE IN ANIMALS WITH VARYING BODY TEMPERATURES

ILLUSTRATION:

Under conditions of controlled temperature, illumination, and humidity the metabolic rate in poikilotherms fluctuates as a function of time. These fluctuations in metabolism, with time, under controlled conditions, contain the same periods as those of the external physical environment. Poikilotherms in their natural physical environments possess adaptively adjusted rhythms of their various activities which are reflected in metabolic rate changes. Since their periodic patterns tend to persist even in constant conditions in the laboratory, metabolic rate is a function of time under these laboratory conditions. The common periods for these persistently recurring patterns of biological activity are the solar day, the lunar day, the synodic month, and the year. These rhythms appear normally to depend upon the external cycles of such common factors as light, temperature, and ocean tides for establishing

their phase relationships relative to the actual times of day, lunar day, phase of moon, and through photoperiod, time of year; but once the phases are adjusted the actual period lengths of the recurring patterns are independent of these rhythmic changes in light and temperature. Solar and lunar rhythms of metabolism appear to persist indefinitely, with high mean precision in period length, under constant conditions in the laboratory. The length of the periods are independent of temperature. In the fiddler crab, Uca, for example, O_2 consumption in a persistent daily cycle is 30 to 50% higher at about 6 a.m. than at about 6 p.m., and in a lunar day cycle it is 30 to 50% higher when the moon is at either its highest or lowest altitude than when it is at the horizon.

MAGNITUDE:

The metabolic rate increase for each 10°C temperature rise is called Q_{10}. If the rate is doubled, the Q_{10} is 2, and if it is tripled for each 10°C rise, Q_{10} is 3, etc., the result being an exponential curve which may be described as an exponential function:

$$M_2 = M_1 \cdot Q_{10}^{(t_2 - t_1)/10}$$

where M_2 and M_1 are the metabolic rates at two temperatures, t_2 and t_1. This general equation allows the Q_{10} to be calculated when observations are made at two temperatures that are not 10° apart. For easier calculation the logarithmic form is

$$\log M_2 = \log M_1 + \frac{t_2 - t_1}{10} \cdot \log Q_{10}$$

SIMILAR EXAMPLES:

Many chemical processes are similarly temperature-dependent in that they have a Q_{10} of about 2 or 3. Numerous enzyme reactions are accelerated at this rate by increased temperature. The function of enzymes as organic catalysts indicates that a great similarity exists in the nature of chemical processes inside and outside the body.

Another example of the influence of temperature on the rate of body processes is the change in chirping rate in a cricket caused by temperature variation.

SAMPLE PHYSICAL ANALOGS:

In the general sense, any temperature-dependent physical or chemical process is analogous to the examples described above. The expansion of gases or metals, for example, with temperature increases is well-known.

The change of transistor properties in relation to temperature and the changes in resistivity of metals or thermistors are also analogs.

METABOLIC RATE IN POIKILOTHERMS, Continued:

Electronic circuits that can operate effectively within a wide range of temperatures, using capacitors and resistors with low temperature coefficients and thermistors to compensate for changing transistor characteristics, would correspond to survival of cold-blooded animals during wide temperature variations.

Another analog would be a temperature-compensated watch which is a passive mechanism, as contrasted with the active or dynamic mechanism of temperature regulation.

REFERENCES: 116, p. 160; 129, p. 38.

Physical Class	Physical Operator	Section 17
Chemistry Heat and Thermodynamics	Sensors Internal Transformers Energy Information Matter	Thermal Sensitivity

OPTIMUM AND EXTREME TEMPERATURES

DESCRIPTION:

All animals have an optimal temperature range within which they can most successfully carry on their activities and their geographical distribution is governed to a great extent by this. Whenever the environmental temperature varies from this optimum range, the organism becomes progressively handicapped. At extremes of temperature, life is not possible. The temperature range at which organisms remain active is somewhat less than that at which life is possible, as is illustrated by the existence of hibernating animals.

ILLUSTRATION:

The optimum temperature range varies from one species of organism to another, and temperatures that would be fatal for one organism are well within the optimum range for another. These differences undoubtedly arise by adaptation. However, rapid change of environmental temperature might be fatal to an organism, while gradual changes might not.

In describing the effects of extreme heat and extreme cold, Davenport states that the effect of high temperatures is mainly chemical, involving the living plasma, or protoplasm, and that the effect of low temperature is mainly mechanical, involving the water content of the body.

Although animals vary in their endurance to extreme heat, it is known that proteins coagulate and become denatured and enzymes are inactivated at a high temperature of about 50°C. This inactivation frequently starts at about 40°C and proceeds more rapidly as the temperature rises. If the thermal destruction of proteins and enzymes goes beyond a certain point, it cannot be alleviated by lowering the temperature. The lethal temperature of an animal depends not only on the temperature but also on the duration of its exposure; this is substantiated by the fact that enzyme inactivation is also dependent on these two factors.

As an animal's body temperature decreases, its metabolic processes become slower, oxygen consumption decreases, and the animal becomes lethargic. Although excessive cooling of the body may be fatal, the degree of cooling that can be tolerated is extremely variable. Many animals can withstand a temperature below 0°C, but if the temperature drops too low or is extended over a long time, the water in some animal tissues will freeze and form ice crystals. This is fatal to most animals.

OPTIMUM AND EXTREME TEMPERATURES, Continued:

In warm-blooded animals the adaptation to temperature variation has been achieved through regulation of internal temperature, while in cold-blooded animals the adaptation enables them to survive even though the body temperature changes.

If the temperature in a tropical fish aquarium drops well below room temperature and remains at this low level overnight, the fish will die. On the other hand there are fish that live normally in water close to 0°C. Penguins, certain species of fish, and other forms of animal life found in the polar regions, are good examples of adaptation of animal life to extreme cold.

Subfreezing temperatures are not always fatal. Many lower animals have been cooled to a temperature of -183°C in liquid oxygen and even to -269°C in liquid helium and have survived. One of the methods for storage of numerous types of microorganisms is in liquid nitrogen.

The amoeba has a much smaller temperature range. When an amoeba is subjected to gradually increasing temperature, at first it becomes more active as it extends its pseudopods. Later, it withdraws its pseudopods entirely to the point at which it exposes the least amount of its body surface. As the temperature continues to rise, the amoeba finally dies because of the coagulation of its protoplasm. If, however, the temperature is slowly lowered from the optimum, the pseudopods remain extended, movement becomes more and more sluggish, and finally, the animal freezes in an expanded condition.

MAGNITUDE:

A great many land animals, such as mammals, birds, reptiles, and insects have a lethal upper limit of about 45°C. The highest tolerance to temperature is found in animals that live in hot springs, e.g., protozoans and mosquito larvae have been found thriving at 50°C. Aquatic animals, which have a lower heat tolerance than land animals, may die if the temperature goes up to 30°-35°C. Some arctic animals may die if the temperature is raised to only 10°C.

SIMILAR EXAMPLES:

Plants also have an optimum and extreme temperature range. This range of temperature within which plants are able to grow may be designated by three temperature points, viz., the minimum, or temperature below which no growth takes place, the optimum which is usually considered the temperature which gives the highest rate of growth or is the best for growth, and the maximum temperature, above which no growth takes place.

SAMPLE PHYSICAL ANALOGS:

Physical and chemical effects due to reduced or elevated temperatures are not so much analogies of low or high temperature effects in animals as they are the causes of these effects.

OPTIMUM AND EXTREME TEMPERATURES, Continued:

Notwithstanding this, the temperature-operating range of physical equipment is usually restricted to specified limits for satisfactory operation. More generally, physical devices have the characteristic of optimum operating range over all measurable variables. For example, a lead sulfide cell for infrared detection produces output signals for a limited portion of the total electromagnetic spectrum. Even more directly analogous are germanium diodes which fail to function properly at both high and low temperatures, and are even permanently damaged if operated beyond certain limits.

The adaptation of organisms to high temperatures might conceivably be compared to the heat treatment of metals.

REFERENCES: 63, p. 237; 129, p. 40; 144, p. 760.

Physical Class	Physical Operator	Section 17
Chemistry Electricity and Magnetism Heat and Thermodynamics	Sensors Contact Internal Actuators External	Thermal Sensitivity

TEMPERATURE REGULATION IN HOMEOTHERMS

DESCRIPTION:

Mammals and birds as homeothermic (warm-blooded) animals maintain an almost constant body temperature. The variation from species to species is not great, being only a few degrees at most. However, mammals have developed means by which they can compensate for or regulate these temperature changes. These compensations can be either physiological, as in the case of man, or partly anatomical, as in the case of fur-covered animals.

The physiological basis of the temperature-regulating mechanism is generally the same for all homeotherms. Usually, the cooling of the body is counteracted by increased heat production while overheating is prevented by evaporation of water or sweating. Not all animals are able to do this, and therefore some animals accomplish this evaporation of water by panting, which consists of the evaporation of water from the tongue and upper respiratory tract.

ILLUSTRATION:

The means for regulation of temperature in man varies for heat and cold as follows:

COLD: Man (whose body temperature is 37.5°C) feels comfortable within the narrow external temperature of 27° to 31°C, and since his body temperature usually does not change, the heat produced during metabolism is given off to the surroundings.

If the surrounding temperature is cooler than 27°C, his body loses heat faster than it is produced. The only way he can maintain his body temperature is to produce more heat, and this is done by involuntary muscle contractions called shivering. The colder it is, the more heat he must produce to keep up with the rate of cooling, and therefore the more he shivers. Toward the lower end of the range, the body also attempts to decrease the heat loss by reducing the amount of blood circulating to the skin.

HEAT: When the surrounding temperature is higher than 31°C, the air is not cool enough to remove the heat produced by man's metabolism, and the only way he can cool the body is to evaporate water by sweating. The higher the temperature, the more he must sweat. In addition to perspiration as a method of cooling in the upper limits, the body sends as much blood as possible to the skin to become

cooled.

When a dog becomes very hot, it will perspire slightly, but the primary cooling is achieved by panting, or the evaporation of water from the tongue region. This evaporation rate is increased by the passage of more air over the wet surfaces due to an extremely rapid respiration rate. Cattle and sheep sweat and pant to some extent, but not as efficiently as man and dog.

MAGNITUDE:

The extent to which man can regulate his body temperature in both the upper and lower limits of the ranges of 27° to 31°C depends almost entirely on two factors: the exposure temperature and length of time or duration of exposure to the unusual conditions. Generally speaking, within this "thermoneutrality range" the blood flow process is sufficient to adjust the rate of heat loss to heat production, while outside the range, shivering and sweating are employed.

The normal respiration rate in a dog is about 15 to 30 breaths per minute, but during panting it increases to over 300 per minute. Simultaneously, the respiration becomes very shallow. If it did not, the ventilation would increase considerably, and the loss of CO_2 from the lungs and bloodstream would be excessive.

SIMILAR EXAMPLES:

The Alaskan ground squirrel has a lower thermoneutrality limit of about 10°C; below this it must increase its metabolism to maintain a high body temperature.

An Alaskan husky has a heavier coat of fur which insulates him so well that his metabolic rate increases only when the temperature drops below 0°C.

SAMPLE PHYSICAL ANALOGS:

See comments on Physical Analogs in General in Section 5, "Equilibrium Sensing and Control", in which equilibrium regulators are described. Also, the water-circulating system in an automobile engine and radiator is similar to the use of blood circulation for cooling purposes. A thermostatically controlled heating or cooling system is also analogous.

REFERENCES: 116, pp. 238-240; 257-258; 129, pp. 44-45.

Physical Class	Physical Operator	Section 17
Heat and Thermodynamics	Sensors: Contact, Internal; Actuators: External	Thermal Sensitivity

TEMPERATURE REGULATION IN POIKILOTHERMS

DESCRIPTION:

Poikilothermic (cold-blooded) animals maintain a body temperature close to the same temperature as their surroundings. If the temperature of the surroundings changes, so does the body temperature of the poikilotherm. This does not mean that these animals cannot regulate their temperature at all; they can and do seek out warmer spots in their environment and thus change their body warmth to some extent. They lack the extensive physiological mechanisms employed by homeotherms (warm-blooded animals) to maintain a virtually constant body temperature.

ILLUSTRATION:

In general, compensation for cold by acclimatizing reactions is more marked in aquatic than in terrestrial poikilotherms, although it does occur in snails and some insects (e. g., cockroach). Metabolic heat is used to varying extents for temperature regulation by colonial Hymenoptera and termites. In winter most colonial Hymenoptera cluster together and the temperature of the cluster may be kept well above the air temperature.

Absorption of radiant heat from the sun is another means of raising body temperature in poikilotherms. This method of temperature regulation is correlated with pigmentation; a light colored snout beetle, Compus niveus, absorbs 26% and a dark carrion beetle, Silpha obscura, absorbs 95% of the infrared impinging on it. A dark brown grasshopper on sunny desert sand remains 4 to 5% warmer than a light buff grasshopper.

MAGNITUDE:

The temperature of an occupied termite mound may be 14° to 18°higher than an unoccupied region. Thus colonial insects utilize physical and chemical means in maintaining relatively constant temperature of the nest.

SIMILAR EXAMPLES:

See entry on "Temperature Regulation in Homeotherms".

SAMPLE PHYSICAL ANALOGS:

Partial temperature regulation is achieved by poikilotherms in that activity liberates heat, warming the animal; cooling is achieved behaviorally or by accident of coloration. In most physical devices, operation of the device is accompanied by a liberation of heat which can, under some circumstances, increase the operating efficiency of the device. For example, rapid discharge of a battery at low temperatures liberates heat due to the internal resistance of the battery. The heat causes an

TEMPERATURE REGULATION IN POIKILOTHERMS, Continued:

increase in temperature, which increases the emf of the battery.

Temperature regulation in some physical devices is also obtained by coloration. Some satellites have been painted with reflective paints to maintain internal temperatures within a desirable operating range.

REFERENCES: 116, pp. 252-256.

Physical Class	Physical Operator		Section 17
Chemistry Heat and Thermodynamics	Sensors Contact Internal	Transformers Energy Actuators External	Thermal Sensitivity

THERMAL INFLUENCE ON ANIMAL BEHAVIOR

DESCRIPTION:

Environmental temperature changes can act as stimuli to different organisms by influencing their behavior to a great extent.

Temperature limits the distribution of animals and at the same time determines their rate of activity. The range of environmental temperatures on earth is much greater than the range permissive of actual life. In general, life activities occur only within the range of about 0°C to 40°C; most animals live within much narrower limits; some survive but are inactive below 0°C. Since temperature is a measure of molecular agitation, it limits the rate of chemical reaction, and it is one factor in the control and influence of animal growth and behavior.

ILLUSTRATION:

Frogs usually swim at the surface of the water, but if the air temperature drops to about 50°F, they will go to the bottom of the water. This regulating effect may possibly be due to temperature inversions in the water.

Cricket chirping rates vary with temperature changes. During the hot summer months when the temperature is high, the chirping sounds are both rapid and high-pitched. When the weather is colder, as in the fall, winter and early spring, the chirping rate is much slower and the frequency is lowered to a point at which it sounds like a rattle.

MAGNITUDE:

The relationship between the cricket's chirp and the surrounding temperature is fairly linear and the following mathematical formulae have been derived for calculating the environmental temperature after first determining the chirping rate. In all three formulae, T = temperature in degrees Farenheit and N = the number of chirps per minute.

1. The temperature formula for the tree cricket, Oecanthus niveus is:

$$T = 50 + \frac{N-92}{4.7}$$

2. For the house cricket it is:

$$T = 50 + \frac{N-40}{4}$$

3. For the katydid, Cyrtophyllus perspicalis, it is.

THERMAL INFLUENCE ON ANIMAL BEHAVIOR, Continued:

$$T = 60 + \frac{N-19}{3}$$

SIMILAR EXAMPLES:

Temperature has a marked influence on the size, form, and general structure of plants just as the range of temperature influences the behavior of animals. When plants are kept constantly under low temperature, the length of the growing zone increases but the internodes remain short, resulting in a plant of comparatively low stature. On the other hand, when they are kept under high temperature, the length of the growing zone decreases, the internodes become longer and the plants become taller.

SAMPLE PHYSICAL ANALOGS:

Almost any temperature-dependent physical or chemical effect is analogous to these effects in animals, but it is evident that there can be amplification of temperature effects by the nervous systems of some animals. A thermometer is an analog of the effect of temperature change on cricket chirps.

REFERENCES: 36, pp. 202-203; 45, p. 720; 63, pp. 240-241.

Physical Class	Physical Operator	Section 17
Aerodynamics Heat and Thermodynamics	Transformers Energy	Thermal Sensitivity

THERMAL INFLUENCE ON INSECT FLIGHT

DESCRIPTION:

The frequency with which insects move their wings varies with many factors, primarily differences in species, age and temperature. Insects have a special thermal problem because of their high rate of metabolism during flight. If an insect is cold, its muscles cannot contract fast enough to carry it in flight; however, it can increase the temperature of the flight muscles by contractions similar to shivering in man.

ILLUSTRATION AND MAGNITUDE:

Successful flight by insects is not possible unless the internal temperature attains a critical value, which may differ from one species or individual to another.

Observations of Vanessa showed that during the first few seconds of flight, when the thoracic temperature was rising, the amplitude of the wing stroke increased from 120° to 180° of arc. Also, with Bombus, an increase in stroke amplitude was noted

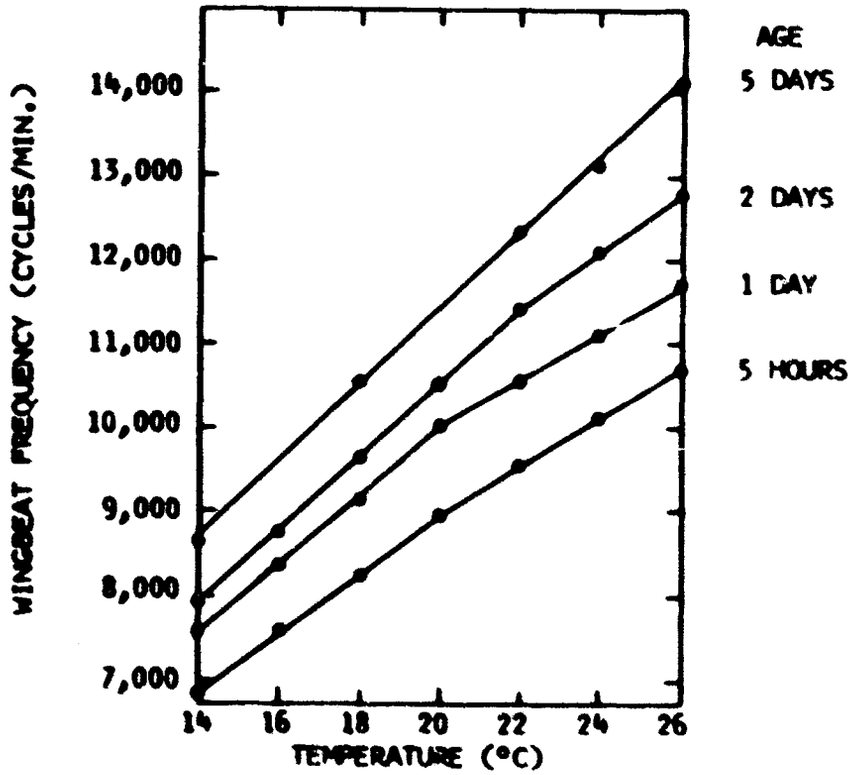

FIG. 26 WINGBEAT FREQUENCY OF DROSOPHILA AS A FUNCTION OF AGE AND TEMPERATURE. D. MELANOGASTER FEMALES IN MOIST AIR AT 760 mm. Hg. (UNPUBLISHED DATA OF WILLIAMS AND CHADWICK.)

during the warming-up period preceding flight. When the temperature of the thorax was only 20°C, the amplitude rose to 120°.

The frequency of the wing beat of Drosophila influenced by temperature is represented by the figure of Williams and Chadwick.

SIMILAR EXAMPLES:

Insect flight may also be altered by various other sensory and environmental factors. Fleshflies buzz about more rapidly and with higher frequencies when stimulated by the smell of meat. Another example is the behavior of bees and hornets when disturbed and ready to sting. Flies and hawk moths hovering over flowers move the wings at lower frequencies during stationary flight than when shifting from one spot to another.

SAMPLE PHYSICAL ANALOGS:

The underlying factor involved in the necessity for a warm-up period by insects is the metabolic rate. As in other cold-blooded animals, the metabolic rate of flying insects is dependent on environmental temperature when the insects are at rest, and repeated contraction of the muscles serves to warm them. In this respect all temperature-dependent chemical reactions constitute analogs of the thermal influence on insect flight muscles.

With respect to function, the warm-up period used for piston-driven aircraft is analogous to that employed by insects, since an aircraft engine warm-up also increases the power output of the engine.

REFERENCES: 19, pp. 591-603.

Physical Class	Physical Operator		Section 17
Heat and Thermodynamics Mechanics	Sensors Contact Distance	Actuators External Internal	Thermal Sensitivity

THERMAL INSULATION IN BIRDS

DESCRIPTION:

Insulating fat layers under the skin of birds help maintain body heat in cold weather, while the body is covered with down feathers which trap air for further insulating effect. Skin feathers automatically fluff the larger and heavier feathers, causing them to stand erect, thereby increasing the thickness of insulation in cold weather.

ILLUSTRATION:

As the air temperature drops, various insulating mechanisms in the bird will maintain its body temperature until the critical temperature is reached. In winter, the amount of insulation increases, that is, the skin feathers are denser, the fat content of the skin increases, and the metabolic rate speeds up.

MAGNITUDE:

Birds maintain a higher and more variable temperature than mammals. Adult mammals range roughly between 36° and 39°C, while birds range from 37.7° to 43.5°C, the majority of them from 40° to 42°C.

SIMILAR EXAMPLES:

Bears and whales have thick insulating layers of fat. In hairy animals, hairs stand erect in cold weather to provide a thermal insulating effect.

SAMPLE PHYSICAL ANALOGS:

The role of the autonomic nervous system in the erection of feathers or hairs for temperature regulation suggests thermostatic action. The use of erecting feathers or hairs on arctic clothing as a means of temperature regulation might be considered as a possibility. Also, compressed air could be used to "ballon out" clothing as a related technique, or exhaust the "ballooning" effect depending upon activity and temperature. Pad-like areas could be individually inflated.

REFERENCES: 18, p. 74; 116, pp. 244-245, 263-264.

Physical Class	Physical Operator	Section 17
Heat and Thermodynamics	Sensors Contact	Thermal Sensitivity

THERMORECEPTORS

DESCRIPTION:

In humans there are two types of thermoreceptors which transmit temperature stimuli as sensations of heat or warmth and cold.

a. Caloreceptors transmit sensations of heat or warmth, lie deeper in the skin, and are less numerous than receptors for sensations of cold. These caloreceptors are found in greater numbers on the forehead, cheeks, and palms of hands than on the rest of the body surface.

b. Frigidoreceptors transmit sensations of cold to the brain. They lie closer to the surface of the skin and are also more numerous than the caloreceptors. The location and relative number of these cold receptors brings them into a close association with the touch receptors in the skin.

ILLUSTRATION:

The research on thermoreceptors by Goldscheider showed the presence of distinct warm and cold sensitive spots over definite small areas on the surface of the human body. Microscopically, he found separate distinct nerve terminals corresponding to the warm and cold loci.

MAGNITUDE:

Results of temperature differentiation studies over the human body indicate the following degrees of difference which can be registered:

Eyelids, 1/20° C
The lips, 1/10°C
Outside surface of arm, 1/4°C
Palm of hand, 1/2° C

SIMILAR EXAMPLES:

The many Golgi-Mazzini corpuscles found in the cornea and conjunctiva of the eye are considered frigidoreceptors since these two parts of the eye are sensitive to cold.

Ruffini endings are quite numerous in the eyelids which are particularly sensitive to heat, and thus are classed as caloreceptors.

SAMPLE PHYSICAL ANALOGS:

Thermal receptors such as a thermocouple or thermistor provide signals proportional to temperature.

REFERENCES: 144, p. 760.

SECTION 18:

SPECIAL LAWS

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Physical Class	Physical Operator	Section 18
Chemistry Mechanics	Transformers Matter	Special Laws

LAW OF BIOGENESIS

DESCRIPTION:

The biogenetic law or the theory of recapitulation relates the developmental history of the individual to the evolution of the race. The former is said to parallel the latter; in other words, "ontogeny recapitulates phylogeny".

Organic evolution, that is, the evolution of one organism from another, is now accepted as an established fact. Evolutionists do not claim that the more complex forms have evolved directly from the simpler animals, but that their ancestors were related. Evidence for this exists in embryological as well as chemical data.

ILLUSTRATION AND MAGNITUDE:

Lower vertebrates, such as fish, have a heart which is composed of two main chambers: the auricle which receives blood from the body, and the ventricle which pumps it out to supply the whole body. In amphibians, which compose the next higher group, the auricle is divided into two parts while the ventricle remains undivided, resulting in three chambers. In reptiles, such as crocodiles and alligators, the heart consists of four chambers, which carries over to all adult birds and mammals. The pertinent feature is that this progression from two to four chambers parallels very closely the successive embryonic stages in the development of the heart of tne individual bird or mammal.

Biochemical analysis contributes to the theory also in the investigation of chordate evolution. It has been found that, with one exception, invertebrate tissue contains arginine phosphate; vertebrate tissue contains creatine phosphate. The tissues of an intermediate form, the protochordate Dolichoglossus, have both phosphates, however. Likewise, the echinoids which show embryological similarity to some protochordates, have both phosphates. The evidence supports the view that chordates have evolved from a stock close to that of the echinoderms.

SIMILAR EXAMPLES:

a. Ernst Haekel's law of biogenesis states that the development of the individual recapitulates the evolutionary stages of the race. He considered the ancestor of the many-celled animals to be a two-layered sac similar to a gastrula, which he called the gastraea. The coelenterates were considered to be slightly modified gastraea.

b. Fritz Müller supported a similar view on the basis of the following evidence. Generally, he found that not all Crustacea arise from the egg so nearly like the adult as does

LAW OF BIOGENESIS, Continued:

the crayfish which emerges almost in the adult stage. The others pass through the various stages of development that are quite similar to the adult stages of other crustaceans.

c. Von-Baer's law describes the development of embryos of different kinds of organisms which are at first similar but diverge from one another at different stages in their embryonic development. On the basis of the closeness of their relationships, those which are least closely related diverge first.

SAMPLE PHYSICAL ANALOGS:

Biogenetic laws are uniquely characteristic of growing systems. Except for crystal growing, our knowledge and utilization of nonliving systems is quite limited. One effect observed in crystal growths, which is reminiscent of some characteristics of biological systems, is that, if a crystal is grown on top of a second crystal with a different lattice structure, it will tend for the first few layers to assume the crystal structure of the base, rather than its own structure.

REFERENCES: 1, pp. 33, 198; 58, pp. 507-510; 148, pp. 371-373.

Physical Class	Physical Operator	Section 18
Mechanics	Transformers Energy Matter	Special Laws

JORDAN AND KELLOGG'S LAWS OF DISTRIBUTION

DESCRIPTION:

Jordan and Kellogg formulated three laws which govern the distribution of animal life. They are: Every species of animal life is found everywhere unless

a) it was unable to get there;
b) having arrived there, it was unable to stay; and
c) having arrived, it became modified into another species.

ILLUSTRATION AND MAGNITUDE:

An example of the first law is exhibited by the fact that, although there are over 450 species of hummingbirds in South and Central America, there are none in Africa. This is not because Africa is in itself unfavorable to hummingbird occupation, but rather that these small birds have never been able to cross the wide oceans which separate their usual habitat from Africa.

In relation to the second law, a number of years ago the U. S. Government transported a herd of camels to the semiarid region of the Southwest and allowed them to run wild in the hope that they would multiply, spread and eventually form a valuable addition to a region inhospitable to most large animals. Their new environment was very much like that from which they had come, so the experiment might have been successful; however, local cowboys periodically put them through their paces so the camels could not survive.

A classic illustration of the third law was cited by Charles Darwin in "The Origin of Species", concerning animals on the Galapagos Islands off the northwest coast of South America. Twenty-six species of land birds were found on these islands. Of these, 23 species are similar to, but still specifically different from, those inhabiting continental land a few hundred miles away. Darwin explained this by the supposition that when the Galapagos group of islands were separated from the mainland in recent geological times, a new habitat was formed on certain islands where various members of the continental species were isolated. In the course of time, 23 of these isolated species gradually changed until each had become sufficiently divergent to warrant being considered a different species.

SIMILAR EXAMPLES:

Another relationship which influences animal distribution is that between expansion and repression. In detail, the relationship is that each species originated historically from some preceding species at some definite place, and its current distribution is due to the interactions of two opposing forces,

JORDAN AND KELLOGG'S LAWS OF DISTRIBUTION, Continued:

expansion and repression.

SAMPLE PHYSICAL ANALOGS:
The distribution laws of Jordan and Kellogg are also applicable to gases. These laws are qualitative, however, and more precise statements of expansion rate, and rate of chemical reaction are available for gases.

REFERENCES: 144, pp. 79-81.

Physical Class	Physical Operator	Section 18
Chemistry	Transformers Energy Information Matter	Special Laws

MENDEL'S LAWS OF INHERITANCE

DESCRIPTION:

Gregor Mendel applied the methods of statistical analysis to the factors involved in breeding. His law of independent assortment reflected the fact that there is an independent assortment of the genes determining the different characteristics in the offspring. Size and color, for example, are independently inherited.

ILLUSTRATION:

Mendel experimented with monohybrids as well as the more complex polyhybrids. One of the investigations involved crossing two peas, one producing yellow round seeds and the other producing green wrinkled seeds. The first generation offspring produced only yellow round seeds indicating that these were the two dominant characters. However, after self-fertilization such hybrid plants produce offspring with seeds showing all possible combinations: yellow round, green wrinkled, as well as yellow wrinkled and green round. This would show then that the intervening first generation offspring contained both sets of genes although the yellow round characteristics were dominant. The new combinations of yellow wrinkled and green round are evidence for the independent assortment phenomenon.

One variation of these laws occurs when the hybrid shows a different condition from either one of the parents. For example, on crossing the red and white races of the four o'clock (Mirabilis jalapa), the progeny are neither red nor white but rather an intermediate pink flower.

In other cases, rather than offspring showing an intermediate characteristic, the hybrids will show the characters of both parents; neither character is recessive. In short horn cattle, for example, red and white parents produce roan, a color which results from an interaction or mosaic of both the red and white hairs in the coat.

MAGNITUDE:

The typical ratio of the hybrid relationships is 3:1, that is, 75% dominant to 25% recessive individuals. When crossing pure tall and short varieties of peas, Mendel obtained 787 dominant (tall) and 278 recessive (short) individuals, a ratio approximating 3:1.

SIMILAR EXAMPLES:

Mendel's law of segregation further amplifies the description of the breeding process. Each gamete or reproductive cell contains genes for only one characteristic. When hybrids are

MENDEL'S LAWS OF INHERITANCE, Continued:

inbred, for example, the offspring consist of hybrids as well as the parental types in pure form. Therefore, it must be that the factors or genes which determine the characters are sorted out or segregated for reproductive purposes so that hybrids can produce the pure parental type individuals.

PHYSICAL ANALOGS:

See the entry on "Law of Natural Selection of Species" for an analog of the genetic process.

REFERENCES: 148, pp. 319, 321-322.

Physical Class	Physical Operator	Section 18
Chemistry Electricity and Magnetism Mechanics	Transformers Information Matter	Special Laws

LAW OF NATURAL SELECTION OF SPECIES

DESCRIPTION:

Natural changes and mutations tend to be retained or discarded depending upon their value to the individual or the species. In 1859 Charles Darwin emphasized this fact, which may be stated in more detail as follows: Of the range of different individuals which make up a population of given species, those individuals having certain characteristics contribute more offspring to the succeeding generation than those having other characteristics. If such characteristics have an inherited basis, the composition of the population is thereby changed to more fully incorporate these characteristics. The successful variants and their progeny are said to be "related" by a natural process.

ILLUSTRATION:

The development of the eutherian (placental) mammals illustrates the phenomenon of natural selection. Changes in the structure of four sets of characters occurred. 1) Many of the mammals became larger. This was especially advantageous for warm-blooded animals in cold climates since it reduced the relative area of heat loss. 2) The limbs grew longer and the number of toes was reduced so that locomotion was facilitated. 3) The number of teeth was reduced and the overall shapes became specialized by the addition of cusps for cutting edges in carnivorous animals and by fusion to form transverse or longitudinal grinding ridges in herbivorous animals. 4) The brain became more developed; specifically the nonolfactory part of the cortex and the frontal lobes increased allowing for more complicated behavior and memory requirements.

MAGNITUDE:

The factors underlying the evolutionary process are more obscure when it is realized that some animals remain nearly unchanged for long periods---for example, opossums and shrews for 80 million years, lemurs and tarsiers for 50 million years, pigs and tapirs for 35 million years and deer for 20 million years.

Human evolution has progressed at a fairly rapid rate. Proconsul, the man-like ape that preceded man, appeared about 500,000 years ago. The first Neanderthal man appeared approximately 50,000 years ago and the first modern man 25,000 years ago.

SIMILAR EXAMPLES:

Lamarck's laws of evolution preceded Darwin in time and were significantly less readily accepted. His first law, which is basically sound, stated that constant use of an organ leads

LAW OF NATURAL SELECTION OF SPECIES, Continued:

to its strengthening whereas disuse leads to its weakening and eventual disappearance.

The second law, however, was highly questioned. He maintained that acquired characteristics are preserved by heredity and passed on to future generations.

Also see "Mendel's Laws of Inheritance" in this section.

SAMPLE PHYSICAL ANALOGS:

A simple experiment with numbers has been devised which illustrates to a degree the mechanics of natural selection. Taking a set of, say, 10 integers as a population, let the rule of combination be multiplication. Let the second generation consist of the last digit of the product of ten randomly selected pairs of digits from the first generation. After several generations, it is evident that most (or all) of the digits will be even numbers (provided that the first generation contained some even numbers). Eventually, it is expected that the entire population will evolve into a set of zeroes. Hence, in this experimental "population", the property of evenness is more dominant than oddness, and the property of being a zero dominates both evenness and oddness.

REFERENCES: 132, pp. 292-293; 148, pp. 380-382; 153, pp. 575-576.

SECTION 19:

SPECIAL EFFECTS

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Physical Class	Physical Operator	Section 19
Chemistry	Transformers Matter	Special Effects

COMPETITIVE INHIBITION

DESCRIPTION:

This type of inhibition may occur in situations in which two processes compete for some raw material used by both. It results in inhibition of one process and diversion of available supplies of the raw material to the other.

ILLUSTRATION:

The keenest competition that most animals have is with others of their own species. This is true, not because they are usually actively hostile toward each other, but because the needs and desires of all individuals in the same species are practically identical. In each of the fundamental requirements of life -- food, air, light, space, mates, and protection -- an individual is rivaled by members of its own kind more than by any other kind, because the individuals of other kinds will usually desire a different kind of food, breathe in different ways, prefer another light intensity, or hunt, nest and hide in different situations. The competition with other forms will in most cases decrease the more and more distantly related they are.

MAGNITUDE:

The degree of competitive inhibition varies inversely with the quantity of any available material which is mutually sought by two processes or animals. In other words, the greater the quantity the lower will be the degree of competitive inhibition.

SIMILAR EXAMPLES:

A similar example to the above inhibition is an enzyme-catalyzed reaction. The natural substrate can prevent the formation of the enzyme-inhibitor complex; or if this complex is already formed, can displace the inhibitor from the enzyme surface.

The rate of competitively enzyme-catalyzed reactions depends only on the ratio of the amount of inhibitor to the amount of substrate.

SAMPLE PHYSICAL ANALOGS:

In bistable electronic circuits, a form of activity occurs that could be compared to competitive inhibition. One tube or transistor in a flip-flop circuit conducts and prevents the second tube or transistor from conducting. When the flip-flop is triggered, it momentarily permits the second tube or transistor to conduct, cutting off or inhibiting the first completely.

COMPETITIVE INHIBITION, Continued:

REFERENCES: 1, p. 59, 102, pp. 442-443; 116, p. 600.

Physical Class	Physical Operator	Section 19
Chemistry Heat and Thermodynamics Mechanics Optics and Light	Sensors Contact Distance Internal Transformers Energy Information Actuators External	Special Effects

ENVIRONMENTAL CHANGE RESPONSE

DESCRIPTION:

Changes which occur in an environment can be the source of stimuli that act on an animal to produce various responses.

ILLUSTRATION:

Some animals change internally to conform to the environment. For example, poikilotherms respond to temperature changes by varying internal temperature. Others maintain relative internal constancy in a changing environment by means of regulatory mechanisms. Measurements of conformity and regulation can be extended to all the physical factors of the environment. In general, conformers tolerate wide internal variation, but narrow environmental limits, whereas regulators tolerate only narrow internal variations but a wider environmental range.

The stick insect Carausius typically becomes pale on a light ground and dark on a black one, through hormonally excited exoskeletal pigmentary changes elicited visually. Coupled with this feature is the akinesis response through which the stick insect is ordinarily immobilized on bushes in the day time, and the unique external morphology which reduces its visibility to common predators. Conditions such as akinesis are reflex responses to environmental stimuli such as light and mechanical stimulation.

MAGNITUDE:

The sweat glands in man respond to environmental changes. At rest, visible sweating usually commences at an environmental temperature between 80° and 90° F.

SIMILAR EXAMPLES:

The hibernation period of bears is a period during which all their body processes are slower. This period is a more general and longer lasting response of the bear to cold weather.

SAMPLE PHYSICAL ANALOGS:

All systems that are strongly coupled to the environment exhibit responses to changes in the strongly coupled variables. The wide variety of animal responses to environmental changes precludes the possibility of a simple model of this effect. However, analogs of some of these effects are given in Section 17, "Thermal Sensitivity".

REFERENCES: 116, p. 4; 144, p. 750.

Physical Class	Physical Operator	Section 19
Aerodynamics Mechanics	Sensors Contact Transformers Information Actuators External	Special Effects

INITIATION OF FLIGHT IN INSECTS

DESCRIPTION:

The process of flight in insects can be started by the interruption of tarsal contact between the insect's feet and the surface on which it is standing. Once it has begun, flight is maintained by wing stimulation sense organs, especially in insects with two pairs of wings, and by sensory organs in the area where the head is attached to the rest of the body.

ILLUSTRATION AND MAGNITUDE:

Experimental studies have shown that insects will rest quietly when they are standing on the surface of some moving object, just as they would on a stationary object. However, when the surface is abruptly removed, the insect immediately starts moving its wings for flight. This reaction ends in flight in almost every case in which it is observed.

SIMILAR EXAMPLES:

A somewhat similar situation is observed in birds which have been trained to perch on a finger or forearm. The arm and hand can be moved freely without disturbing the bird, but the abrupt removal of the "perch" will initiate immediate flight.

REFERENCES: 36, p. 29; 116, p. 302.

Physical Class	Physical Operator	Section 19
Chemistry Fluid Mechanics Mechanics	Transformers Matter	Special Effects

MEMBRANE PERMEABILITY

DESCRIPTION:

The permeability of a membrane is the extent to which molecules can pass through it. All membranes have selective permeability, i.e. certain substances pass through it more or less easily, and to others it is impermeable. The size of the particle with respect to the size of the membrane pores and, in the case of ions, the electric charge are fundamental factors in the permeability of the membrane.

ILLUSTRATION:

Membranes of the tissue cells generally are permeable to water, or to OH^- or H^+ ions or both, and to HCO_3^- ions. Chloride ions pass readily into and out of certain cells, such as erythrocytes and cells of the gastric mucosa, yet muscle cells contain exceedingly small quantities of Cl^- ions.

MAGNITUDE:

Cell membranes generally are made up of an organized and oriented lipid layer superposed upon a meshwork of protein layers, the lipid and protein layers being held together by forces of adsorption and by complex formations between them. The lipid layer of the erythocyte membrane is about 50 Å thick, equal to the thickness of two to four lipid molecules. The thickness of the membrane lipid layers of other cells appears not to exceed 100 Å. The thickness of the protein layers is less well known; however, it probably is something of the same order of magnitude.

SIMILAR EXAMPLES:

See entry entitled "The Sodium Pump and Electrical Potential".

SAMPLE PHYSICAL ANALOGS:

Filters using filter paper or porous porcelain provide a gross selective action on particles in solution or suspension since particles smaller than a given size pass through a filter. Membrane permeability is more complex than the filtration process, however, since ionic charge may be involved. The action of a screen grid in a vacuum tube is analogous to the rejection of ions by a membrane.

MEMBRANE PERMEABILITY, Continued:

REFERENCES: 147, pp. 113, 594-595.

Physical Class	Physical Operator	Section 3
Chemistry Electricity and Magnetism Mechanics	Transformers Energy Actuators External Internal	Special Effects

MUSCLE CONTRACTION BY ELECTRICAL IMPULSE

DESCRIPTION:

In many organisms, there are highly differentiated, elongated cells which have the ability to shorten and thicken. These cells are the muscle fibers, and this type of action is called contraction. The muscle is an organ formed of a bundle of such contractible fibers. Among invertebrates the fibers of a muscle are loosely associated, but in the vertebrates they are bound together and enveloped by special tissues. The typical vertebrate muscle is surrounded by a connective tissue sheath. Muscles respond to many kinds of stimuli, but in physiological conditions, striated muscles are excited by nerve impulses, but electrical stimulation also produces the contraction.

ILLUSTRATION:

Muscles, especially skeletal muscles, are composed of a large number of functionally independent single fibers, each having a threshold independent of that of any other fibers. Thus an impulse applied to a whole nerve may be strong enough to excite only a few of the individual fibers, in which case a weak contraction would be evoked. A stronger impulse will cause excitation in a larger number of fibers, and the summed response will be greater. If the impulse is large enough, all the fibers will undergo contraction and a further increase in the strength of the impulse will produce no greater contraction.

MAGNITUDE:

The interval between the beginning of the electrical impulse and the attainment of maximum contraction marks the duration of the contraction process and is called the contraction time. The contraction times of various skeletal muscles vary considerably, and these differences serve as a basis for a classification of muscles into "slow" and "rapid" types. In the cat the following contraction times (in milliseconds) have been obtained:

soleus, 100 ms
medial head of gastrocnemius, 40 ms
extensor digitorum longus, 40 ms
internal rectus of the eye, 7.5 to 10 ms

SIMILAR EXAMPLES:

Muscle contraction can be provoked experimentally by chemical, thermal, and mechanical as well as electrical stimuli. Also, chemical and thermal stimuli are particularly important in the case of such related effects as amoeboid movements, ciliary

MUSCLE CONTRACTION BY ELECTRICAL IMPULSE, Continued:

movements, and tropisms in unicellular organisms

SAMPLE PHYSICAL ANALOGS:

Artificial muscles based on protein-like chemical structures have been devised. More recently, a bladder device that expands laterally and contracts longitudinally upon inflation has been devised by Howard A. Baldwin of the Laboratory for the Study of Sensory Systems, Tucson, Arizona.

REFERENCES: 23, pp. 884-886, 905; 68, p. 793.

Physical Class	Physical Operator		Section 19
Fluid Mechanics Mechanics	Transformers Energy	Actuators Internal	Special Effects

PERISTALSIS

DESCRIPTION:

Peristalsis is the "wormlike" movement by which the alimentary canal in higher animals propels its contents. It consists of wave-like contractions which are produced by surrounding coats of smooth muscle lining the alimentary canal.

ILLUSTRATION:

The process of peristalsis is produced by a contraction of the circular muscles of the walls of the alimentary canal. The movement of a food bolus, according to Bayliss and Starling, is described by stating that the "law of the intestine" is constriction on the oral side and relaxation on the anal side of any stimulated point. The contraction is usually more prominent than the relaxation. Peristalsis is well marked in the oesophagus and stomach. In the latter it occurs during digestion soon after a meal and begins again some hours later as "hunger" contractions.

MAGNITUDE:

Peristalsis waves follow each other rhythmically every 15 to 20 sec; they take from 15 to 30 sec to travel down the stomach, and continue as long as there is food in the stomach.

SIMILAR EXAMPLES:

The vasoconstriction of blood vessels, usually arterioles, is a similar example in that they become narrow due to the constriction of the smooth muscles in their walls. Also see "Pumping Action of the Heart", and "The Flame Cell as a Pump".

SAMPLE PHYSICAL ANALOGS:

A peristaltic tubing pump is one analog in which the tubing is pressed together and released in a manner serving to move material through it. The action is roughly comparable to that of an aspirator bulb in which the valving is replaced by pressing the tubing together and releasing it with a motor and drum.

A similar device could be based on a "muscular valving" technique developed by Howard A. Baldwin of the Laboratory for the Study of Sensory Systems, Tuscon, Arizona. This would involve the use of artificial sphincter muscles to produce wave-like contractions to mix the contents of the tubing and move them along the tubing. Baldwin's muscle device for linear contraction is noted under "Muscle Contraction by Electrical Impulses".

PERISTALSIS, Continued:

REFERENCES: 1, p. 176; 7, pp. 689-694, 68, pp. 343, 373, 377.

Physical Class	Physical Operator	Section 19
Fluid Mechanics Mechanics	Sensors Internal Actuators Internal	Special Effects

VASOCONSTRICTION

DESCRIPTION:

Vasoconstriction is the decrease in diameter of the blood vessels, usually arterioles, resulting from contraction of smooth muscles in their walls. These muscles are mainly controlled by the sympathetic nervous system. The capillaries apparently constrict by a change in shape of the endothelial cells. This process of vasoconstriction provides certain physiological adaptations in the case of tension, shock, or generally in cases where emergency to the organism is sensed.

ILLUSTRATION AND MAGNITUDE:

An underfilled state of blood vessels as may result from hemorrhage or shock, or any condition which tends to cause a fall in blood pressure, will result in vasoconstriction to adjust the vascular capacity to reduce blood volume and thus maintain the blood pressure.

Studies on the correlation between frequency of stimulation of the vasomotor area and vasoconstrictor response showed that an increase in frequency of the stimuli from 0 to 6 impulses/sec resulted in an almost linear rise of the peripheral resistance and a vasoconstriction amounting to 80 to 85% of the maximal effect.

This vasoconstriction produced at frequencies in this range will disappear within 4.5 to 5.5 sec after cessation of the stimulation.

SIMILAR EXAMPLES:

The process of peristalsis is somewhat similar to vasoconstriction in that there is a contraction of smooth muscle. See entry on "Peristalsis".

SAMPLE PHYSICAL ANALOGS:

Vasoconstriction can be viewed as one element in a feedback control system. See the Physical Analogs in General for the section "Equilibrium Sensing and Control" for a discussion of control systems.

REFERENCES: 1, p. 241; 31, pp. 1134-1135.

Physical Class	Physical Operator	Section 19
Chemistry Fluid Mechanics Mechanics	Sensors Internal Transformers Matter Actuators Internal	Special Effects

WATER BALANCE IN AQUATIC INSECT METABOLISM

DESCRIPTION:

The problem of water balance in aquatic insects is the same as in other aquatic animals, invertebrate or vertebrate. In fresh water there is danger of loss of salt to the hypotonic environment, or gain of water through the body surface or in feeding. In brackish water osmotic stress is reduced, but the insect usually has to cope with an environment with fluctuating salt content and with ion ratios differing from those in the body fluid. A sea-water environment is reasonably constant, but, since it is usually hypertonic, it tends to withdraw water from, or donate salts to, the blood.

ILLUSTRATION:

The simplest type of regulation occurs in the larva of the alder fly, Sialis. In which the osmotic pressure of the blood is approximately 1% sodium chloride and the normal plasma chloride varies between the concentrations in 0.15% and 0.34% sodium chloride solutions. In the Sialis, water balance is maintained by a combination of active excretion of water through the Malpighian tubes plus active absorption of electrolytes from the environment.

MAGNITUDE:

In Sialis the primary defense against salt loss appears to be a permeability to outgoing chloride so low that six week's starvation in distilled water is required to lower the plasma chloride to the equivalent of a 0.06% sodium chloride solution.

SIMILAR EXAMPLES:

Under normal circumstances, insects seem to regulate their water balance in much the same way as mammals, if not perhaps within quite so narrow limits. If there is a dissimilarity between the two groups, it is rather in the greater ability of insects to endure accidental or forced changes.

REFERENCES: 15, pp. 199-200.

Physical Class	Physical Operator	Section 19
Chemistry Fluid Mechanics Heat and Thermodynamics	Sensors: Internal Actuators: Internal Transformers: Matter	Special Effects

WATER BALANCE IN KANGAROO RATS

DESCRIPTION:

The kangaroo rat (Dipodomys) is a rodent which can survive for long periods of time without drinking water. This animal thrives on seeds and other dry plant material, eats little or no green food, and can survive drinking sea water.

ILLUSTRATION:

The bodies of kangaroo rats contain as much water as those of other animals (an average of 66%). Although they may have eaten only dry food for weeks or months, the water content remains the same, their water loss never exceeding their water gain. The animals have no sweat glands and do not need water for heat regulation since they are nocturnal animals that avoid the heat of the day and search for food only during the cool night. Evaporation from the lungs is inevitable, however, and is the greatest single source of water expenditure in the kangaroo rat. The feces on the other hand, have a very low water content and take only a small fraction of the available water.

MAGNITUDE:

The kangaroo rat can excrete salt in a concentration twice that in sea water.

SIMILAR EXAMPLES:

The camel's slow rate of water loss, combined with his unusual tolerance to dehydration of the body, maintains a water balance similar to that of the kangaroo rat.

REFERENCES: 129, pp. 62-63.

SECTION 20:

SPECIAL PHENOMENA

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Physical Class	Physical Operator	Section 20
Electricity and Magnetism Materials Properties Mechanics	Sensors Internal Transformers Energy Actuators Internal	Special Phenomena

THE ALARY MUSCLES OF INSECTS

DESCRIPTION:

Contraction of the alary muscles of some insects facilitates the diastolic phase of the heartbeat. The muscles are developed differently in various insect species and even in different stages of a single species. Observations do not indicate a uniform action of the alary muscles, but variously reveal their functioning as elastic elements or as muscles that actively contract in rhythm, maintain a steady contracted state, or do not contract at all.

ILLUSTRATION:

In larvae of Chironomus the alary muscles definitely play an active roll in heart dilatation. In this insect, in which the heart action can be observed through the cuticle, the alary muscles are found to contract rhythmically and synchronously with each other, although their action is not quite in synchrony with the heartbeat. When the alary muscle contraction is in phase with diastole, the heart dilatation is exaggerated. After dilation a contraction of the heart muscle occurs as a reaction to the mechanical stimulation exercised by the tension. The early systolic refractory period is presumed to maintain the regularity of the heartbeat.

MAGNITUDE:

The number of alary muscles present in insects varies from one insect to another. There are 12 pairs of alary muscles in Periplaneta, 4 pairs in the hive bee, 3 pairs in Haematopinus, and 2 pairs in the larva of Chironomus.

SIMILAR EXAMPLES:

The flight muscles of insects resemble these alary muscles in their reflex type of reaction to external stimuli.

REFERENCES: 6, pp. 247-249; 70, pp. 151-153.

Physical Class	Physical Operator	Section 20
Chemistry	Transformers Matter	Special Phenomena

AXIAL GRADIENT

DESCRIPTION:

Axial gradients are graded regional differences in living organisms, involving metabolism and conditions associated with or resulting from it. The gradients appear to be primarily quantitative and constitute the earliest known stages of organization characteristic of physiological axes. These axes are imaginary lines representing the gradient patterns and later organization. In general, the region of highest rate of activity in animal eggs, embryos and other reproductive bodies becomes the apical end or the head of the larvae, or later stages or both.

ILLUSTRATION AND MAGNITUDE:

The Planaria illustrates the theory of axial gradients. The primary axis or axis of polarity is an imaginary line extending from the anterior to the posterior end of the body. In Planaria the head has a relatively high rate of metabolism and dominates the rest of the body. Experiments have shown that a gradient of metabolic activity proceeds from the anterior to the posterior end. For example, if planarians are cut into four pieces, the anterior piece will be found to use up more oxygen and give off more carbon dioxide than any of the others; the second piece comes next in its rate of metabolism; the third piece next; and the tail piece gives the lowest rate of all.

When a planarian is young, it is relatively short and its whole body, expecially the head, has a relatively high rate of metabolism. As it grows older, it becomes longer and its whole metabolic rate slows down. When young, the high metabolic rate of the head was able to exercise a dominance through the transmission of stimuli down the gradient over the entire length of the animal. With a slowing down of the metabolic rate of the apical end and an increase in the length of the path over which the impulse travels, there comes a time when the apical end can no longer maintain a physiological dominance over the entire axis. At the point where dominance fades out, an independent part of the body arises through what is known as physiological isolation. The isolated piece, the second zooid, has its own gradient, the metabolic rate of the anterior end being the highest. This region now becomes a new apical end or, morphologically speaking, the head of a new zooid. No structure indications of a new individual are visible, however, at this time. The only tests of the presence of a second or third individual are physiological tests. The isolated posterior zooid now forms a new head, with eyes, brain, and other parts. The new head then reorganizes the rest of the piece into a complete new individual.

AXIAL GRADIENT, Continued:

SIMILAR EXAMPLES:
The axial gradient phenomenon is similar to the process of regeneration. See section on "Regrowth and Repair".

REFERENCES: 58, pp. 213-214.

Physical Class	Physical Operator	Section 20
Chemistry Electricity Magnetism	Sensors Internal	Special Phenomena

THE BIOLOGICAL CLOCK

DESCRIPTION:

The term biological clock refers to the phenomenon of pacing of activity by an organism in a cyclic manner as related to the environment. The system may be influenced by external factors, primarily light and temperature, to which it may adapt. This clock mechanism is generally assumed to underly such things as the swarming of marine annelids; the migration, meeting, and sexual activity of many animals; and the flowering and vegetating of plants.

ILLUSTRATION:

The orientation of birds under varying conditions gives an excellent illustration of the clock mechanism. Birds that were kept indoors were able to find the proper direction if tested under the artificial sun. No direct information was available so that the bird would be aware of the local time. It was therefore suggested that an internal clock which is synchronized with local time was the relevant cue. Further evidence was obtained when experimenters tried to shift the internal clock.

Birds that had been previously trained were exposed to an artificial light-dark situation, such that their day began and ended six hours later than the normal day. After several days, the birds were tested again. Results were as expected; that is, the birds went in a direction about 90° to the right from the original training route. It was therefore concluded that the internal clock is somewhat guided by the environmental factors. Further experiments with other species yielded similar results.

Various effects have been obtained when temperature rather than light is altered. If a nocturnal animal is placed in an environment which is dark yet constantly oscillating in temperature, it will reset its phase and follow a steady state rhythm with a 24-hour cycle dependent on temperature. The onset of activity in nocturnal cockroaches also will readjust so as to coincide with the highest range of temperatures.

MAGNITUDE:

Rhythmic periods may vary from 1/10 sec for the brain waves of the diving beetle to a year for the reproductive cycle in birds.

In the alga Hydrodicton reticulatum there is evidence that the rhythms of growth and oxygen metabolism are entrained by 12:12, 6:6, 10.5:7 hour cycles of light and darkness, and that the rhythms persist 3 days in darkness with periods of 24, 12, and 17.5 hours respectively.

THE BIOLOGICAL CLOCK, Continued:

The rhythm of petal movement in the flower Kalanchoe blossefeldiana conforms to cycles of light and darkness for 24:24 hours to 6:6 hours, but not to 4:4 and 2:2 hour cycles.

SIMILAR EXAMPLES:

Man displays a similar type mechanism in much of his behavior; however, in this case the environment may play a principal role in the synchronization of rhythms.

For example, evidence from arctic subjects who are periodically exposed to long durations of light or darkness without the normal sunrise or sunset, show that the normal rhythmic pattern of excretory habits disappears. Moreover, in the winter season, when the everyday activity follows a fairly regular schedule, the disorganization of these rhythms is even more extreme. Therefore, the activity patterns themselves do not explain the evidence. The resulting theory places the emphasis on the environmental conditions such that physiological rhythms are more normal when a period of daylight coincides with the normal hours of activity.

SAMPLE PHYSICAL ANALOGS:

Many computing systems employ clocks or timing mechanisms; these timing mechanisms may run at a fixed rate or may be synchronized to some external times. The timing for ignition in gasoline engines is basically cyclic but varies in phase during acceleration according to the carburetor pressure.

REFERENCES: 17, pp. 1-9; 66, pp. 379-387; 79, pp. 265-285; 80, pp. 72-74; 94, pp. 325-332; 126, pp. 1-81; 127, pp. 463-473.

Physical Class	Physical Operator	Section 20
Chemistry Electricity and Magnetism Heat and Thermodynamics	Transformers Matter	Special Phenomena

BIOTYPE SPECIALIZATION

DESCRIPTION:

A biotype is a population of individuals that are identical genetically. The test of genetic purity of a population of a pathogenic fungus is the consistency of its behavior. Most species of plant pathogenic fungi comprise many biotypes, and attempts are made to group the most closely related ones into races and then to group the most closely related races into varieties, which in turn are grouped into species. These specialized biotypes are indistinguishable in structure, but show differences in physiological, biochemical, and pathogenic characteristics.

ILLUSTRATION:

Biotype specialization is illustrated by results of investigation of Puccinia graminis, the fungus that causes stem rust of small grains and grasses.

Puccinia graminis is a species within which there are clearly recognizable varieties, races, and biotypes. There are at least six rather distinct varieties that differ in size of spores and in the kinds of plants they can attack:

1. Triticum (wheat) whose host plants are wheat, barley, and many wild grasses;
2. Secale (rye) whose host plants are rye, barley, and many wild grasses like those attacked by Triticum;
3. Avena (oats) whose host plants are oats and wild grasses different from those attacked by Triticum;
4. Phleumpratense (timothy) whose host plants are timothy and certain wild grasses;
5. Agrostis (redtop) whose host plants are redtop and other species of Agrostis;
6. Poa (bluegrass) whose host plants are Kentucky bluegrass and related species.

Races are known within the varieties Triticum, Avena, and Secale. Although there sometimes are at least slight morphologic differences between races within a variety, the most important and most easily recognizable differences are in the degree of pathogenicity on certain varieties within the genera Triticum, Avena, and Secale respectively.

MAGNITUDE:

More than 200 physiological species of Puccinia fungus have so far been demonstrated.

SIMILAR EXAMPLES:

In linguistics, each major language is identified as

BIOTYPE SPECIALIZATION, Continued:

consisting of sublanguages, called glossas. Each glossa contains a number of dialects. These groupings of languages, glossas and dialects parallel the groupings of species, varieties and races.

SAMPLE PHYSICAL ANALOGS:

Variations in populations arise from the natural selection process. For an analog of the process, see the entry, "Law of Natural Selection of Species".

REFERENCES: 136, pp. 36-38.

Physical Class	Physical Operator	Section 20
Chemistry	Transformers Matter	Special Phenomena

CELLULOSE DIGESTION IN MAMMALS

DESCRIPTION:

Microbes (bacteria and Protozoa) which live in the digestive tract act upon certain materials, which cannot otherwise be hydrolized, to change them into a form suitable for digestion. This is actually a form of symbiotic digestion. This is the process used in the digestion of cellulose inasmuch as the hydrolizing enzyme, cellulase, is not produced by a vertebrate.

ILLUSTRATION:

In the cow and other ruminants, the true stomach is preceded by a large sac called the rumen. Food enters the rumen and there undergoes heavy fermentation; the decomposition products are absorbed and utilized whereas the remaining food is regurgitated and processed again.

In the horse, the fermentation of cellulose takes place in an enormous pouch of the intestine, the caecum. However, it does not have the full advantage of microbial fermentation since the caecum is placed in the hind end of the digestive tract. The dead microbial bodies do not undergo complete digestion and fermentation of the plant fibers is less complete, for there is no remastication of unfermented cellulose as in the cow.

MAGNITUDE:

The bacterial count necessary for cellulose digestion is approximately a billion per milliliter of caecum content.

The rumen itself may accommodate contents up to one-seventh the weight of the ruminant animal itself. The pH of the sheep rumen during digestion is between 5.5 and 6.8.

SIMILAR EXAMPLES:

The South African honey guide, a relative of the woodpecker, exhibits another form of symbiotic digestion. It seems to prefer wood as well as honeycomb. Similarly, bacteria are responsible for the digestion of wood by the honey guides.

SAMPLE PHYSICAL ANALOGS:

Commercial use of bacterial action is made in the treatment of sewage. This process could not be considered symbiotic, but it is an instance of useful application of bacteria.

Biological or bacterial fuel cells have been constructed which employ bacteria to provide electrical power.

REFERENCES: 116, p. 117; 129, pp. 8-9.

Physical Class	Physical Operator	Section 20
Chemistry Fluid Mechanics Heat and Thermodynamics	Sensors Internal Transformers Energy Actuators Internal	Special Phenomena

CHEYNE-STOKES RESPIRATION

DESCRIPTION:

Periodic breathing results from an involuntary disturbance in the regular breathing rhythm. The most common type of this is the Cheyne-Stokes breathing pattern. Regular periods of respiration alternate with periods of temporary suspension. Breathing begins by shallow movements which gradually increase in amplitude; they then gradually decrease and finally cease. After a short interval, the cycle begins again.

Periodic variations in arterial blood pressure accompany this type of breathing. A loss of consciousness may also be experienced with this phenomenon. Cheyne-Stokes breathing is sometimes seen in infants during sleep. It is often involved in adaptation to high altitudes. In hibernating animals and aquatic mammals, it is a normal occurrence.

ILLUSTRATION:

The most widely accepted explanation for Cheyne-Stokes breathing is as follows: Anoxia diminishes the excitability of the respiratory centers, leading to apnea. This increases anoxia sufficiently to stimulate the chemoreceptors in the carotid and aortic bodies thereby leading to a reflexive increase in the excitability of the center; carbon dioxide is accumulated during the period of apnea until the concentration is reached which is high enough to stimulate the respiratory center. Respiration begins again so that anoxia and carbon dioxide concentration lessens and apnea occurs.

The underlying mechanism involved here may be the respiratory center in the medulla. In newborn infants the medulla is not yet in control of the spinal centers; hence, this phenomenon occurs frequently in infants. Similarly, the fact that this is more frequently experienced during sleep or under drugs which depress the central nervous system gives further evidence for this theory.

MAGNITUDE:

The periods during which there is a temporary cessation of breathing last for about 35 seconds.

The effects of Cheyne-Stokes respiration may alter the venous pressure. It may rise to 180 mm H_2O during the phases of cessation of breathing, perhaps due to the low content of CO_2 in the blood.

SIMILAR EXAMPLES:

There are many types of periodic breathing. In Bist's

CHEYNE-STOKES RESPIRATION, Continued:
breathing, for example, the periods of breathing terminate abruptly, rather than gradually decreasing as with the Cheyne-Stokes process. There is also much greater irregularity in the duration of each period. Bist's breathing may occur in cases of meningitis and has much more serious significance than the Cheyne-Stokes phenomenon.

SAMPLE PHYSICAL ANALOGS:

The timing mechanism in respiration is undoubtedly produced by a biological clock which has a rate dependent upon CO_2 level in the blood and by other parameters. Hence, it should be possible to construct a timing device which simulates this dependence on other variables.

REFERENCES: 7, p. 174; 68, pp. 303-304.

Physical Class	Physical Operator	Section 20
Optics and Light	Sensors Transformers Distance Information	Special Phenomena

CONSTANCY PHENOMENON

DESCRIPTION:

Constancy is a phenomenon of perceptual recognition whereby the psychological factors of the stimulus situation outweigh the physical characteristics which are actually affecting the sense organ. The parameters of object size, color and shape can all be sensitive to the constancy characteristic.

ILLUSTRATION:

In terms of size constancy, two categories are relevant: first, a known object will always be judged to be the same size although the retinal image may vary considerably, and secondly, the size of an unknown object will be judged on the basis of the size of the retinal image as well as by the perceived distance from the nodal point to the object.

In the latter case, it has been shown that size constancy is largely a function of the cues available to the subject. That is, if there are reliable cues available, the stimulus will be judged close to its actual physical size no matter what the intervening distance is. If black drapes or some other material is placed so as to eliminate almost all cues, the subject relies primarily on visual angle (retinal image) and this results in inaccurate information.

MAGNITUDE:

The formula determining the perceived size of an object is:

$$a = A/D$$

that is, the retinal area a subtended by an object varies directly with the object area, A, and inversely with its distance D.

One experiment to test these hypotheses had the subject stand at the intersection of two long corridors arranged in an L-shape. The comparison disk was placed in one corridor 10 ft. away from the subject; in the other corridor was a similar disk arranged at various distances (10-120 ft), always large enough to subtend a visual angle of 1°. The task was to adjust the size of the comparison stimulus so it appeared equal in size to the standard one. In cases of binocular and monocular vision, there was good size constancy. When an artificial pupil was added, however, eliminating accessory depth cues, the settings were midway between the laws of size constancy and visual angle. If the spot was 50 ft away, according to size constancy, it would appear about 10 in, whereas according to visual angle results, it would appear about 1 in. With an artificial pupil, the subject approximated the size to be about 5 in, whereas with black drapes which naturally eliminated all cues, size was

CONSTANCY PHENOMENON, Continued:

judged to be about 3 in.

SIMILAR EXAMPLES:

Another instance where the psychological parameters of the stimulus dominate the physical characteristics is seen in the closure phenomenon. This is mainly a principle of Gestalt psychology. It indicates the act of mentally completing a physically incomplete figure. This results in the perception of a "good Gestalt", a familiar form with definite meaning.

SAMPLE PHYSICAL ANALOGS:

Pattern recognition devices have been described which have some of the properties of constancy, i.e., which are only partially sensitive to object size. These devices also exhibit a tendency to ignore defects in figure shapes and, hence, exhibit a tendency to closure.

REFERENCES: 110, p. 134; 149, pp. 480-487.

Physical Class	Physical Operator	Section 20
Chemistry	Transformers Matter	Special Phenomena

CONVERGENCE

DESCRIPTION:

As animals of different ancestry have adapted similar modes of life, they have tended to become similar in some of their features. There are innumerable instances in the animal kingdom of animals that look alike externally and yet are fundamentally different. This approximation of dissimilar stocks is called convergence.

ILLUSTRATION:

Moths and birds are obviously different groups of organisms. However, the hummingbird and the humming moth exhibit such similarity in habits and functional operation that they have been mistaken for each other very frequently when observed from a distance.

SIMILAR EXAMPLES:

Parallelism is a type of evolutionary phenomenon similar to convergence in many respects. It is demonstrated in those groups which are similar in adaptation and structure, and still undergo independent evolutionary changes in the same direction. For example, the coiled oyster, Gryphaea, differs from most other oysters not only in its overall coil-like appearance, but in some internal characteristics also. However, all the different species of oysters, including Gryphaea, exhibit the evolutionary parallelism which allows them to be classified as of one group.

SAMPLE PHYSICAL ANALOGS:

A common restraint condition can produce similarity of behavior in learning machines from initially dissimilar conditions.

Also, dissimilar learning machines can learn the same solutions to problems in similar environments.

REFERENCES: 135, pp. 67-69.

Physical Class	Physical Operator	Section 20
Fluid Mechanics	Actuators External	Special Phenomena

THE FLAME CELL AS A PUMP

DESCRIPTION:

The flame cell is a large hollow cell with flickering cilia, extending into the central cavity, that create a current which forces material in solution through the tubules. This type of cell forms the excretory system of the planaria and of members of the phylum Gastrotricha.

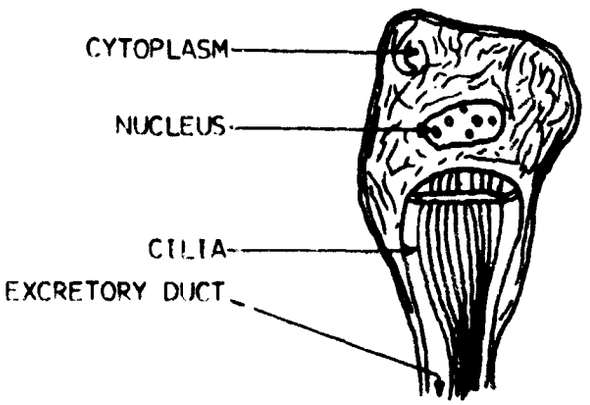

FIG. 27 THE FLAME CELL

ILLUSTRATION:

The flame cell of the planaria acts as a liquid pump. The pumping action is controlled by three sets of muscles, a circular layer just beneath the ectoderm, external and internal layers of longitudinal muscle fibers, and a set of oblique fibers lying in the mesoderm.

Contraction and relaxation of these muscles at different times creates a current and forces material in solution through the tubules.

SIMILAR EXAMPLES:

Other examples of biological pumps include (1) the heart as a variable pump and (2) peristalsis. The flame cell is the reverse of microorganisms that move through fluid using cilia or flagella. In the flame cell, water is moved through the cell by this mechanism. In the vertebrates ciliated cells are used to whip small particles along tubes, as in the windpipe and its small branches in the lungs; here, inhaled dust is whipped along by wave-like motion of cilia.

SAMPLE PHYSICAL ANALOGS:

There could be some applications for the type of mechanism employed by the flame cell, such as a fuel pump or a water pump. Air blowers may possibly be another workable application for such

THE FLAME CELL AS A PUMP, Continued:

devices. However, attempts to scale up the size of the flame cell will quite likely result in devices less efficient than existing pumps or blowers.

REFERENCES: 18, p. 113; 57, p. 153.

Physical Class	Physical Operator	Section 20
Mechanics	Sensors Contact Actuators External Transformers Information	Special Phenomena

GROUP BEHAVIOR OF FISH

DESCRIPTION:

A school of fish is a group-type of social organization to which the fish are bound by rigorously stereotyped behavior and even by anatomical specialization.

Schooling fish do not merely live in close proximity to their kind, as many other fish do; they maintain, during most of their activity, a remarkably constant geometric orientation to their fellows, heading in the same direction, their bodies parallel and with virtually equal spacing from fish to fish. Swimming together, approaching, turning and fleeing together, all doing the same thing at the same time, creating an illusion of a single animal moving in a sinuous path through the water.

ILLUSTRATION:

Constant observation under laboratory situations has shown that schooling is a gradual process. It develops initially from the interaction of two larvae or fry. The visual stimulation seems to be the determining factor. The original head-on approach gives way to the head-to-tail approach. During the original head-on situation, the visual pattern is changing, the head and eyes coming constantly closer. When approaching the tail, however, the fry simply sees a small silvery stripe undulating in front of him.

T. C. Schneirla has hypothesized that in general mild stimuli are attracting whereas intense ones are repelling, even without any prior exposure to the situation. This seems to be the principle underlying the fry's behavior.

Moreover, the two attributes, visual attraction and schooling behavior, seem to arise simultaneously. In fact, fish which cannot see, cannot school. A fish blinded in one eye approaches and aligns himself with another fish only on the side of the intact eye.

The visual cue which seems most important is movement rather than color and/or species. The typical spacing between them being a function of the amount of visual attraction or repulsion.

MAGNITUDE:

About 2,000 species of marine fish school, as well as a major group consisting mainly of the freshwater fish, Cyprinidae, that contains at least 2,000 schooling species.

When newly hatched fry from 5 to 7 mm in length approach others within 5 mm, they dart away; at 8 to 9 mm, two fry school momentarily if one approaches the tail of the other; at 9 to 10.5 mm, the head-to-tail approach is primary and two fry will school

GROUP BEHAVIOR OF FISH, Continued:

for 5 to 10 sec; at 11 to 12 mm, the fry will begin to school normally in groups ranging between 30 and 50 fish.

SIMILAR EXAMPLES:

The migration of birds is similar to schooling in several ways. It is a mass activity of a group; also it seems somewhat instinctive in that young birds which have never migrated before will leave after the older ones and yet follow the same route. The parallel situation occurs when fry reared in isolation inevitably form schools when placed together.

SAMPLE PHYSICAL ANALOGS:

The complete causal chain involved in instinctive activities includes optical sensors, a controller, and a built-in behavior pattern much like a fixed computer program. For further information on control systems, see the section "Equilibrium Sensing and Control".

REFERENCES: 33, p. 302; 133, pp. 128-138.

Physical Class	Physical Operator	Section 20
Chemistry Electricity and Magnetism	Transformers Information	Special Phenomena

INSTINCT IN INSECTS

DESCRIPTION:

Instinct in insects is the unlearned response of the insect to a single or to several stimuli, and consists of coordinated reflexes which are complex chains of tropisms. Stimuli are received both from without and from within the insect.

Instincts in insects are executed without prevision or without experience or training, and are therefore not associated with reasoning. They are complex reflexes in response to numerous chemical or physical stimuli, proceeding in a regular sequence characterized by rhythm and repetition. Generally they are inflexible but submit feebly to modification.

ILLUSTRATION:

The reactions of insects can seldom be attributed to a single reflex. It has been shown that the egg-laying instinct of Drosophila melanogaster is not the result of a single stimulus but follows a chain of responses incurred by stimuli such as odor, moisture, taste, and touch. Simple reflexes thus combine to form an instinctive act.

In general, the responses of insects are inflexible. All mud daubers of the same species inhabit the same type of location, provision their nests with the same kind of food, and employ the same type of architecture.

MAGNITUDE:

Instinctive action reaches high degrees of complexity in such insects as wasps, spiders, bees, and ants. Instinct is probably manifested to a greater degree of complexity in the insect than in any other life form.

SIMILAR EXAMPLES:

Learning provides a survival mechanism in higher forms that progressively replaces instinct in the evolutionary sequence toward man. Some instincts must await maturation before they are manifest, and for this reason may sometimes be confused with learning in such animals as the cat or chimpanzee.

SAMPLE PHYSICAL ANALOGS:

In function, the action of a digital computer under the control of a coordinated set of instruction lists is quite similar to the action of an insect under instinctive control. The repetitive nature of instinctive action is similar to the action of a computer in a loop. Instinctive actions are subject to

INSTINCT IN INSECTS, Continued:

interruption as are some real-time computer programs.

REFERENCES: 36, pp. 219-221; 154.

Physical Class	Physical Operator	Section 20
Mechanics	Sensors Transformers Internal Information	Special Phenomena

INTEROCEPTORS

DESCRIPTION:

Interoceptors are sensory receptor organs within the animal body which receive stimuli originating in the body. They are located in linings of the digestive system and are stimulated by conditions in this system.

ILLUSTRATION:

Hunger and thirst are two distinct sensations associated with the digestive apparatus for which adequate sense organs have not yet been discovered.

Hunger may result either from nutritional "poverty" in the blood, or from the contractions of the stomach which occur (normally) rhythmically at a given time after meals or at a certain state of emptiness of the stomach. These contractions are believed to stimulate certain receptors in the muscular stomach wall. The conditions which make the stomach contract are largely unknown.

Thirst results from stimulation of receptors by dryness of the membranes of the pharynx caused by an increase in salt concentration in the blood. Also there are receptors within the hypothalamus which are sensitive to changes in the blood. The reaction of these receptors to a high salt concentration also causes the sensation of "thirst".

MAGNITUDE:

Muscular contractions produced by stimulating the interoceptors of the digestive system usually last from 2 to 5 minutes, but may be as long as 15 minutes. These receptors are more sensitive in young robust individuals than in older persons.

SIMILAR EXAMPLES:

Although appetite is not usually considered as a "sense", it has been described occasionally as "the memory of food enjoyment" brought about by internal changes connected with such external stimuli as the sight, odor, or taste of food.

SAMPLE PHYSICAL ANALOGS:

The Reron and Artron devices, developed by Lee, have a goal to keep an internal storage battery charged. Dissipation of the stored electrical energy in this battery causes a drop in battery potential which, through the goal circuit, reduces the degree of conditioning of the Reron or Artron and increases the tendency to explore or experiment.

REFERENCES: 57, pp. 412-413. 81; 82. 83. 144, p. 753.

Physical Class	Physical Operator	Section 20
Heat and Thermodynamics Mechanics	Actuators External	Special Phenomena

MODIFIED FUNCTIONS OF INSECT WINGS

DESCRIPTION:

Insect wings often serve for purposes other than their primary one of flight. They may serve for protection, for temperature regulators, and for auxiliary activity in the mating process.

ILLUSTRATION:

In many groups such as Blattaria, Hemiptera, and Coleoptera, the forewings are modified to a greater or lesser degree to act as protective coverings for the second pair of wings and the body. In these species, the forewings often retain an active part in flight; in other cases, however, as with many beetles, these are merely held passively out of the way, perhaps acting as gliding surfaces or stabilizers.

Further modification is apparent in the activity of the Bombus. This creature is stimulated to warm itself with vibrations of the wing muscle when transferred to a colder temperature. Both temperature and ventilation are controlled in this way by apis in the hive.

MAGNITUDE:

If the Bombus is transferred from a temperature of 20°C to 5°C, it will initiate the vibratory activity of its wing muscles.

Differences of 1.8°C in body temperature have been recorded in butterflies, depending on whether the insect is so oriented as to expose a maximal or a minimal area of the wings to the sun.

SIMILAR EXAMPLES:

The male Drosophila uses its wings in a mating dance. By various vibrations, it may serve to attract its partner and ward off competitors. In Orthoptera, the wings are used to produce sounds which serve as mating signals. They are equipped with certain unique structural modifications for this purpose. Violent mating reactions are evoked when male Aedes are approached with a tuning fork vibrating at a frequency characteristic of the female flight rhythm.

REFERENCES: 19, pp. 608-609.

Physical Class	Physical Operator	Section 20
Chemistry Electricity and Magnetism Mechanics	Sensors Transformers Internal Energy	Special Phenomena

NEUROGLIA CELLS

DESCRIPTION AND ILLUSTRATION:

Neuroglia cells are the supporting structure of nervous tissue which consistsof a fine web of tissue made up of modified ectodermic elements. They are of three types: macroglia or astroglia, oligodendroglia, and microglia.

The macroglia, or astroglia, cells are moderately large cells with numerous processes which radiate out from the cell body. In most instances one or more processes have terminal expansions which attach to blood vessels or the pia mater. The marginal astrocytes together with the pia form the piaglia membrance which invests the brain and spinal cord and accompanies penetrating blood vessels as a cuff to considerable depths. The macroglia cells provide the repair mechanism and replace lost tissue by forming glial scars.

The oligodendroglia cells are somewhat smaller than the macroglia cells and have fewer processes. They are found either in close association with smaller blood vessels, or as satellite cells closely applied to large nerve cells, or in rows between bundles of fibers in the white matter. In the latter situation their processes clasp the nerve fibers. The oligodendroglia cells function in a metabolic role in the formation and preservation of the myelin sheaths of the nerve fibers in the central nervous systems.

The microglia cells are found diffusely through both the gray and white matter. Normally they are small cells, with two or more finely branching feathery processes. They are the scavengers of the nervous system and become actively amoeboid and phagocytic in case of injury and death of the other elements.

The number of glia cells is not known. However, it is known that the neuroglia cells outnumber the neurons by at least two to one in the cortex.

SIMILAR EXAMPLES:

Nerve cells or neurons are similar to neuroglia cells in that the latter may also provide some data processing and may interact with nerve cells.

SAMPLE PHYSICAL ANALOGS:

Some studies of brain structure have been made by R. M. Stewart from the viewpoint of constructing inorganic electrochemical devices that simulate the neuroglial and neuronal lattices. Stewart has related this work to the theory and construction of his MABIAC, an electrochemical apparatus that contains a homogeneous metallic lattice immersed in acid, through which

NEUROGLIA CELLS, Continued:

surface "waves of polarization" similar to nerve impulses propagate and interact. It is possible that the lattice could be fabricated from a large number of small spheres.

REFERENCES: 7, p. 1115; 44, pp. 933-935; 139, pp. 509-514.

Physical Class	Physical Operator	Section 20
Chemistry Fluid Mechanics Heat and Thermodynamics	Transformers Actuators Energy Internal Matter	Special Phenomena

NUTRITIONAL REQUIREMENTS OF INSECTS

DESCRIPTION AND ILLUSTRATION:

Many insects survive and grow on what appears to be an extremely restricted diet. For instance, some termites live in dry wood, wax moths feed on the wax and debris of bee combs, and clothes moths live on wool. In all cases that have been investigated critically, however, it is found that this apparent limitation of diet is not complete, in that the insects require a number of vitamins and sources of organic nitrogen in the form of essential amino acids.

In the case of termites these essential amino acids, vitamins, and organic nitrogen are supplied by microorganisms either in the food or in the bodies of these insects. The termite alimentary canal contains a large number of protozoa, which, in addition to decomposing cellulose, may also provide the essential metabolites that otherwise are absent from the insect's diet.

Cockroaches and various grain beetles have a high degree of independence from these vitamins necessary to the diet of nearly all animals. They have been shown to be dependent on the synthetic activities of yeasts or bacteria which live in the alimentary canal.

MAGNITUDE:

Many insects require a great quantity of one type of food. The larvae of the mealworm will not grow on a diet containing less than 40% carbohydrate, with the best growth obtained from a diet containing 72% carbohydrate.

SIMILAR EXAMPLES:

The necessity of vitamin C to maintain the integrity of the blood capillaries and normal bone and tooth development is similar.

REFERENCE: 101, p. 129; 103, pp. 109-132.

Physical Class	Physical Operator	Section 20
Electricity and Magnetism Mechanics	Transformers Energy Actuators Internal	Special Phenomena

ORIGIN OF THE HEARTBEAT IN INSECTS

DESCRIPTION:

Anatomical evidence suggests in some insects that the heartbeat is of myogenic origin, while other evidence points to a neurogenic origin. There is no current general agreement among investigators on these points.

ILLUSTRATION:

The heart beats of the dragonfly Anox junius, and the silkworm Bombyx mori, are believed to be myogenic in origin since they continue to beat in the absence of ganglion cells. It is, however, difficult to demonstrate beyond doubt that all intrinsic ganglion cells are absent in a heart preparation, and consequently that the heart muscle alone initiates the contraction wave. The hearts of some insects are very well innervated. This innervation can, of course, be responsible for the control and regulation of the heartbeat even if unnecessary for initiating the contraction.

Evidence for a neurogenic heartbeat has been offered by the temperature characteristic. The temperature range in the Periplaneta americana nymph is approximately 15-30°C which is equivalent to 12,000 calories. This specific value is often a factor in studies on invertebrate nervous systems and on structures under nervous control. Insofar as the temperature characteristic of the heart approximates this value, the neurogenic origin is a possibility.

The pharmacologic evidence supporting either view is inconclusive. The total potency of the heart in rhythmic behavior strongly suggests a myogenic beat, and there seems to be no question that the heart is under nervous control. However, the origin of the insect heartbeat is still open to question.

MAGNITUDE:

The speed of propagation of the heartbeat varies among insects and at different times within the same insect. It may be so slow that 3 waves of contractions are visible in the dorsal vessel as in the Corethra larvae, in which the contraction wave moves at not more than 1 mm/sec. On the other hand it may be so rapid that the entire vessel seems to contract simultaneously, as in the Lucanus cervus larvae where the rate of propagation ranges from 19.5 to 44.5 mm/sec with an average of 27.2 mm/sec.

During the larval development of the Sphinx ligustri the contraction rate shows a progressive decrease, from 73-108/min for the first two instars, 50-79 for the third, 33-56 for the fourth, and 28-55 for the fifth.

ORIGIN OF THE HEARTBEAT IN INSECTS, Continued:

SIMILAR EXAMPLES:

The insect electrocardiogram shows a complex wave, usually oscillatory, the significance of the components not being so clear as in the Limulus where the controlling cardiac ganglion can be treated separately from the cardiac musculature. In Limulus also, the electrogram of the pacemaker ganglion shows bursts of impulses corresponding to each heartbeat, thus indication a neurogenic origin. The point of initial activity may vary in location at any one time, the automatism of the heart segments being correlated with the number of associated ganglion cells. In the insect, however, the pacemaker may shift from one end of the heart to another without any noticeable correlation with cardiac innervation.

REFERENCES: 6, pp. 240, 245, 270-272.

Physical Class	Physical Operator	Section 20
Mechanics	Sensors Internal Transformers Energy Actuators Internal	Special Phenomena

PHYSIOLOGICAL COMPENSATION

DESCRIPTION:

Physiological compensation, often reflex in origin, is frequently employed during the function of a sensory or muscular system of one part of the body to restore the normal status function of another part of the body.

ILLUSTRATION:

An illustration of physiological compensation is the maintenance of arterial blood pressure at relatively constant levels by afferent discharge of the pressoreceptors in the aortic arch and the carotid sinus. These receptors continuously monitor the arterial pressure and, through appropriate reflex connections, alter the tonic autonomic discharge controlling both the heart rate and the diameter of the arterioles.

SIMILAR EXAMPLES:

The thermostatic regulation of the mammalian body is similar. A constant heat level is maintained by autonomic reflex arcs which appropriately vary the diameter of the cutaneous blood vessels (through which heat is lost to the environment), the activity of the pilomotor muscles and sweat glands, and the secretion of the calorigenic product of the adrenal medulla, epinephrine.

SAMPLE PHYSICAL ANALOGS:

An analog of physiological compensation occurs in learning machines following the failure of one of the artificial nerves in the learning network. Following a failure, the other artificial nerves, under the action of goal circuits, modify their functioning until proper system action is restored.

REFERENCES: 122, p. 226.

Physical Class	Physical Operator	Section 20
Chemistry Mechanics	Sensors Internal	Special Phenomena

PROPRIOCEPTORS

DESCRIPTION:

Proprioceptors (proprioreceptors) are those sensors that give man information about both his own body and his environment. These receptors are located in the deeper regions of the body and receive stimuli from the region of location.

This class of sense organs also includes the special receptor system which is located in the non-auditory labyrinth of the inner ear and which, through the generation of an elaborate set of postural reflexes, is responsible for the maintenance of general bodily equilibrium.

ILLUSTRATION AND MAGNITUDE:

Since the extensive work of the British physiologist, B. H. C. Matthews, the end organs responsible for initiating proprioceptive messages have been quite well understood. Four sets of receptors are involved, two in muscle proper, one in tendon, and one in the fascia associated with muscle. Matthews has designated them respectively: A_1, A_2, B, and C endings.

A_1 fibers are found to be stimulated by passive stretch of the muscle. Active contraction brings about an abrupt cessation of A_1 activity. A slight tension exerted on the muscle invariably brings the A_1 endings back into play, and a strong, sudden stretch may excite a sufficiently high level of activity to produce sensory impulses from A_1 at frequencies up to 500/sec. About 50% of the fibers in muscle are of the A_1 type.

A_2 fibers are of larger diameter, hence more prompt to report. They provide much the same data as do the A_1 type. They likewise normally respond to stretch by initiating impulses and cease firing upon active contraction of the muscle. However, the terminations of A_2 do show heightened activity during a very strong contraction. This is because they are wound around so-called "intrafusal" fibers, modified red muscle cells, which also contract when the main body of the muscle contracts vigorously. Both A_2 and A_1 fibers will continue to fire with great regularity when the muscle is slightly stretched.

B receptors have higher thresholds than do A_1 or A_2. They respond with some regularity to tension, however it is imposed. Thus they signal both stretch and active contraction.

The C receptors function to report mechanical deformations whether imposed from without ("deep pressure") or from within (muscle movement).

Proprioceptive sensitive measurements on discrimination of motion at joints have been done by Goldscheider. He made a lengthy systematic set of experiments. It was found that of nine joints tested, the shoulder was the most sensitive and the

PROPRIOCEPTORS, Continued:

ankle was the least. Displacements of 0.22 to 9.42° (at a speed of 0.3°/sec) could be discerned at the shoulder. The wrist and knuckle of the index finger were nearly as sensitive (0.26-0.42° and 0.34-0.43°, respectively), while the ankle required relatively larger displacements (1.15 - 1.30°).

SIMILAR EXAMPLES:

Other sensing organs, particularly the ones providing tactile and chemical sensations, are similar in many respects to proprioceptors. Examples of these are contact receptors (which respond to impressions from objects in contact with the body) and gustatory receptors (the receptors for the sense of taste).

See also the entry "Pain Detection".

SAMPLE PHYSICAL ANALOGS:

Strain gages for detecting elongation of materials provide information analogous to the proprioceptors. Goniometers are angle measuring devices which provide signals analogous to proprioceptors in joints.

REFERENCES: 37, pp. 233-239; 68, pp. 901-902.

Physical Class	Physical Operator	Section 20
Electricity and Magnetism Fluid Mechanics Mechanics	Actuators Internal	Special Phenomena

PUMPING ACTION OF THE HEART

DESCRIPTION:

The pumping portions of the heart are the two ventricles, right and left, separated by a muscular septum.

The right ventricle occupies a large part of the ventral or sternocostal surface of the heart. Its right boundary is the coronary sulcus, its left, the anterior longitudinal sulcus. The wall of the right ventricle is about one-third as thick as that of the left ventricle; it is thickest near the base of the heart and gradually becomes thinner toward the apex.

The left ventricle occupies a small part of the sternocostal and about half of the diaphragmatic surface of the heart, its tip forming the apex of the heart. The left ventricle is longer and more conical in shape and its walls are about three times as thick. The interior presents two openings, the atrioventricular guarded by the mitral valve, and the aortic guarded by the aortic valve.

ILLUSTRATION:

The means by which the heart cavities are able to pump the necessary volume of blood from the systemic veins to the arteries and to impart a pressure sufficient to cause a continuous flow of blood through the capillaries can be considered in terms of atrial, ventricular, and arterial pressures, and of variations in the volume and means of emptying the cardiac cavities.

Ventricular contraction initiates the pumping action of the heart. At the beginning of this contraction there is an instant closing of the mitral valve, as the ventricular pressure curve exceeds the left atrial pressure curve. The "C" wave in the atrial curve begins at this time and is due to the rising pressure in the ventricle which is transmitted through the closed arteriovenous valves which bulge into the atrium. This marks the onset of the left ventricular isometric contraction period which consists of a slow and then a rapid phase of pressure rise. The isometric contraction period in which the ventricle is a closed cavity ends at the moment at which the ventricular pressure exceeds the aortic pressure. The aortic valves are forced open as indicated by the onset of the pressure rise in the aorta, and blood is discharged from the ventricular cavity.

From the moment that the aortic valves open until they close, ventricle and aorta are common cavities and, consequently, their pressure pulses have a similar contour. Ventricular volume now starts to decrease. The period of maximum ejection lasts until the peak of the aortic pressure pulse and is followed by a period of reduced ejection which is completed at the

beginning of the incisura. This is the end of ejection of blood and of ventricular systole. The ventricular cavity still retains more than half its original diastolic volume. During protodiastole the pressure within the ventricle continues to decline and this phase ends at the moment of aortic valve closure. Isometric relaxation then follows. At this time, the atrium and ventricle are relaxed and the left ventricular cavity is completely closed off from the atrium and aorta and only partially filled.

During the preceding ventricular contraction, the left atrial pressure undergoes a temporary abrupt decline as a result of an artefact imposed by cardiac movement; however, as blood pours into the cavity of the left atrium from the pulmonary veins, the atrial pressure rises continuously to the end of the isometric relaxation period.

MAGNITUDE:

The quantity of blood ejected by each beat of the left ventricle in the average healthy man during rest is from 70 to 80 cc. An equal quantity is, of course, discharged at the same time by the right ventricle, making a total for the whole heart of from 140 to 160 cc. The contents of the left ventricle are ejected against a much higher mean arterial pressure than the contents of the right; the mean pressure in the pulmonary artery being about 1/6 of that in the aorta.

The heart of an adult of sedentary occupation pumps at least 5500 liters of blood through his body daily.

SIMILAR EXAMPLES:

See "Peristalsis" and "The Flame Cell As A Pump" for a discussion of other biological pumps.

SAMPLE PHYSICAL ANALOGS:

Artificial heart-lung devices used in heart surgery employ pumps quite different in principle from the heart. No portable artificial hearts have been devised at this time; however, at least two are being developed. It appears that it will be a difficult engineering feat to duplicate the pumping capability of the heart in a comparable sized package.

REFERENCES: 7, pp. 242-244, 305; 44, pp. 567-588.

Physical Class	Physical Operator	Section 20
Chemistry	Transformers Energy Matter	Special Phenomena

SYMBIOSIS

DESCRIPTION:

Symbiosis is the living together of two species that can not otherwise exist without each other.

Associations of different species of plants and animals are by no means always an expression of cooperative adaptations. All gradations occur from those which are mutually beneficial to the members of a species, to those in which one member secures all the advantage at the expense of the other.

The most intimate associations in which the organisms involved are mutually benefited, if not absolutely necessary for each other's existence, are termed symbiotic.

ILLUSTRATION:

An illustration of symbiosis is that of the termites and their intestinal flagellates. The termites feed on celluiose contained in wood, but are unable to digest it; the flagellates render the cellulose digestible. Without the flagellates the termites would starve to death in the midst of plenty, as has been proved by depriving termites of their flagellates. The flagellates live on the cellulose eaten by the termites and are unable to exist anywhere except in the termite's intestine.

Less intimate cases of symbiosis occur between crabs, sponges, and coelenterates. Crabs may place sponges on their shell with the result that the sponge is transported from place to place, which may be of advantage to it, and the crab is concealed from its enemies and prey and if detected is not attacked because of the disagreeable qualities of the sponge. Hermit crabs that live in snail shells often place hydroid coelenterates or sea anemones on top of the shell; the nematocysts of the coelenterates drive away enemies and the coelenterates are carried about and probably obtain some of the food captured by the crab. Other examples of symbiosis occur among insects and vertebrates. Ants protect aphids and in return "milk" honeydew from them, which they use as food. Birds remove insects from the backs of buffaloes, rhinoceroses, etc., and warn their hosts of approaching danger.

SIMILAR EXAMPLES:

There is a wide range of similar symbiotic relations. Certain seeds, such as the seeds of leguminous plants, are unable to germinate without an association with a fungus.

From the standpoint of agriculture, there exists a symbiotic relationship between the nitrogen-fixing bacteria and plants.

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SYMBIOSIS, Continued:

These bacteria form small nodules on the roots of higher plants and make atmospheric nitrogen available to the latter, gaining in return adequate nutrition from the plants.

Within the human intestinal tract is the bacterium, Escherichia coli, which acts on food material, thereby aiding in its breakdown.

REFERENCES: 58, pp. 457, 702-703.

Physical Class	Physical Operator	Section 20
Acoustics Optics and Light	Sensors Internal	Special Phenomena

TIME JUDGMENT IN HUMANS

DESCRIPTION:

Time judgment refers to the ability of a person to estimate time. Efficiency in the estimation of time may be judged by attempts to depress a button for a specified number of seconds. In one series of tests, five seconds were estimated accurately, while estimates of one and ten seconds were inaccurate. The efficiency of the subject's time orientation may be judged by success in attempting to depress the button at a specified time of day. Usually, estimations of a fixed period of hours become gradually shorter. In general, humans in isolation have a poor sense of time.

ILLUSTRATION AND MAGNITUDE:

The following experiment was devised to test a person's ability to determine time intervals in hours, and shorter intervals in seconds. The subject was isolated in a dark room for a period of 48 hours. He was required to indicate 4 and 8 o'clock by pushing a button for one second, noon by depressing it for 5 seconds, and midnight by depressing it for 10 seconds. Generally, one second was overestimated, 5 seconds were estimated accurately, and 10 seconds were underestimated. Over a period of 48 hou the 4-hour estimations became progressively shorter. Most persons were unable to estimate time accurately and even became disoriented in relation to time. Some were not able to spend 48 hours in isolation.

SIMILAR EXAMPLES:

A similar time disorientation and lack of ability to indicate time correctly occurs even when the isolated subject is supplied with light and a clock.

SAMPLE PHYSICAL ANALOGS:

Although no satisfactory analog exists for the process of judgment, the data from time judgment experiments suggests a biological clock (for long intervals) that requires external synchronization signals such as those provided by day and night.

REFERENCES: 43, pp. 12-18; 106, pp. 1-13; 112, pp. 1-21.

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MEMISTOR, WIDROW'S
NEURON-LIKE UNIT, BABCOCK'S
NEUROTRON, LEE'S
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