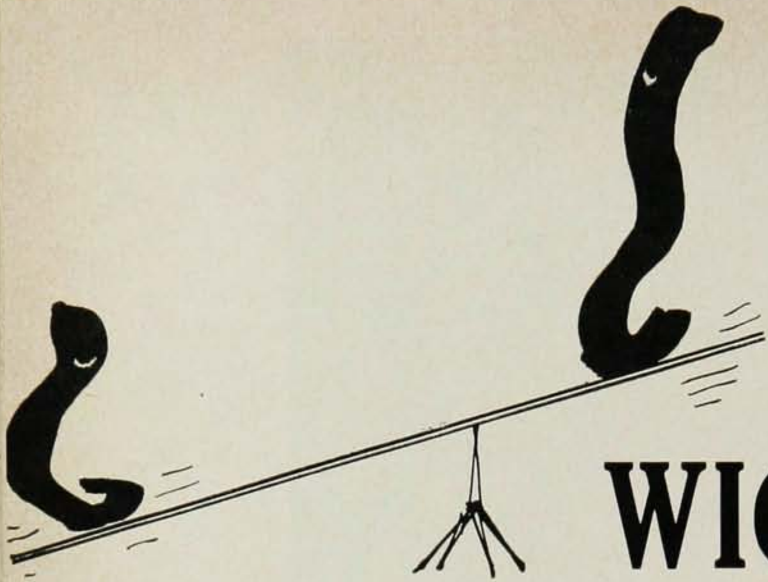

WIGGLEWORM PHYSICS

By Jerome Rothstein

WE know that our picture of the universe is very strongly influenced by our means of perception. Basically, we are eye-hand-coordinated animals. Perhaps our sensory and psychological apparatus prejudices us in favor of some particular picture of the universe, when in reality the picture is warped by being filtered through our particular sensory and nervous equipment. This is, of course, a very old philosophical problem, and one can say that the use of measuring apparatus sensitive to things we cannot observe directly would go a long way toward removing this kind of prejudice. The suspicion remains, however, that intelligent beings very differently endowed than we are might come up with a very different picture of the world. For example, the space-time of such a creature might have a dimensionality different from ours, or other concepts might be basic and lead to a whole different structure from the one we have so painfully evolved over the centuries—often by stripping away prejudices.

In an effort to see how reasonable the possibility that we are all being fooled really is, we shall try to sketch how science might develop for a race of blind, deaf, highly intelligent worms living in black, cold, sea-bottom muck, and possessing only senses of touch, temperature, and a kind of taste (i.e., a chemical sense). These hypothetical creatures are chosen because they seem to be about as different from human beings as they possibly can be and still be able to learn things about their environment. They have no eyes, ears, or hands. They cannot use the sun or the stars to give them notions of time. They do not have natural rulers a "foot" in length because they have no feet, and indeed, their shape is very elastic. As a rule of the game, we impose the condition that the only concepts they can use are those that develop by intelligent and imaginative thinking about the experience available to them. In short, the game must be played consistently with the operational viewpoint.

Wiggleworm Space-Time

The most extreme operational viewpoint must permit the existence of some kind of conceptual arena in which the totality of performable operations are somehow embedded. We are not allowed, at this stage, to identify this arena with our space-time because we have not yet defined operations, such as using rulers and clocks, which underlie the space-time concept. We must somehow or other arrive at that concept in a way possible for a "wiggleworm" * to do, or else we cannot admit space-time into the structure of the wiggleworm's universe.

We have assumed that wiggleworms are intelligent, and that they possess a number of sensory modalities. We can therefore legitimately say that they are in a position to obtain information that has something to do with the world they inhabit. The mere possibility of obtaining such information presupposes the legitimacy

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* This name is chosen to emphasize their purely hypothetical nature; real worms, as far as we know, have nothing to do with wiggleworms.

of a concept we will denote by subjective time. Basically, it is a kind of informational coordinate.

Consider the tactile sense of the wiggleworm (henceforth we refer to him as "Wiggy"). As he wiggles around in the muck, he receives a succession of sensations: the swish of water, the slither of ooze, the shock of contact with a shell or stone, or an encounter with another wiggleworm. In every case, Wiggy is conscious of a sensation or a set of sensations selected from the totality of sensations permitted by his physiology (we can include in the term physiology his "psychology" as well). His information input consists precisely in such a sequence of selections from an ensemble of alternatives. He thus acquires information in the technical meaning of the term used in communication theory. The only part of the technical definition which is not yet satisfied is the assignment of a probability measure for the various sensory inputs. This difficulty need not detain us at this point; as a stopgap measure we can consider that the relative-frequency concept of probability is adequate here. We can say that Wiggy is exposed to a sequence of sensations starting with the dawn of his consciousness and ceasing with his death. In the course of his life there will be some sensations which recur with such frequency as to be grouped together conceptually. It is hard to see how any concepts of the world could be formed unless such groupings were possible and unless there were sufficient memory capacity to allow an abstraction from a set of similar sensations to be formed, which could be taken as constituting a recognizable element of experience.

It is indeed interesting that the basis for subjective time, probability, memory, and the existence of recognizable elements of experience, all come into the discussion virtually at once. We believe this to be inherent in the concepts of information and the operational viewpoint.

To return to subjective time, it seems legitimate to assume that this concept could emerge from Wiggy's awareness of the sequence of sensations he experiences. It seems legitimate to suppose that he is capable of isolating subsets in the succession, which can vary from the simplest elemental act of awareness to a highly structured sensation. The isolation of a particular complex of sensations is a discrete occurrence, and, in the undifferentiated sequence of sensations, such isolated complexes will follow in succession. These complexes, which are the objects of conscious attention, can be put into one-to-one correspondence with a set of consecutive integers. Wiggy must be prepared for surprises and chance events, however, and on the basis of experience would learn that a complex of sensations can forcibly intrude on him, in principle, "between" two such discrete complexes. What do we mean by "between" in this context?

We shall say that a particular sensory complex, complex$_b$, is between complex$_1$ and complex$_2$ if

(a) there is a state of Wiggy's memory which contains information about complex$_1$ and none about complex$_b$ or complex$_2$;

(b) there is a state of Wiggy's memory in which information exists about complex$_1$ and complex$_b$, but none about complex$_2$;

(c) there is a state of Wiggy's memory in which information exists about complex$_1$, complex$_b$, and complex$_2$;

(d) there exists no state of Wiggy's memory containing information about complex$_b$ and none about complex$_1$;

(e) there is no state of Wiggy's memory containing information about complex$_2$ and none about complex$_b$ or complex$_1$.

This concept of informational betweenness thus has an essentially logical definition, given that Wiggy has a memory, and that Wiggy is capable of obtaining information about his world via sensations. As a fish can nip off his tail while he is eating something in the muck, it is clear that his consciousness must admit the possibility of the unexpected, and thus in retrospect, the possibility of sensation complexes having been interpolated between (in the sense defined) any two complexes to which he has given his attention. It is well known that if one permits interpolations of this sort between the integers, they can be labeled by the rational numbers. If Wiggy now considers the totality of all possible finite or infinite sequences of interpolations, he will be led to the topological equivalent of the real numbers (i.e., the one-dimensional continuum). This continuum, which represents a flow of possibilities for information input via sensations, is what we call subjective time. It is irreversible in the sense that a well-defined "direction" exists: the "later" memory state of two states is the one with the larger number of stored memories of complexes or the larger amount of stored information.

Wiggy and we therefore have much in common already: sensations, memory, and subjective time. Furthermore, both his and our subjective times have a "forward" or "future" direction operationally distinguishable from the "backward" or "past" direction.

The subjective time we have discussed so far is really only a small part of what might be subsumed under the title, both for Wiggy and for us. It is but a single part of total awareness, where total awareness includes a complex mixture of the perceived, the sensed, the felt, the remembered, and the streams of conscious and semi- or subconscious associations that embroider multichannel or even single-channel inputs. We are certainly endowed with such a complex kind of awareness; if Wiggy can acquire tactile sensations from a great many portions of his body simultaneously, then he, too, has a complex multichannel sensory input. Indeed, it seems almost necessary to have something a bit more complex than the simple flow of subjective time to permit what might eventually be called measurement. For the time being, the closest we can come to the measurement concept is a well-defined sequence in subjective time, with respect to which other events can be placed by interpolation. The analogy between the marks on a ruler and this "standard sequence" on the one hand, and the interpolated events and lengths to be measured on the other is clear.

In a way, the subjective time heretofore discussed has already had a lot of subjectivity strained out of it; it is a small part of total awareness which one can believe has something to do with an external world. There are two further elements of subjectivity in the concept so far which can easily be eliminated. The first is the question of an origin for the subjective-time coordinate. Clearly, nothing in Wiggy's or our worlds depends on whether we consider a particular sequence of events as being a later portion of an enumeration which started before the particular sequence began, or whether we choose to start the enumeration afresh. There is thus a kind of "translation invariance" to be added to the subjective-time concept in order to make it more subjective.

Another element of arbitrariness in subjective-time enumeration is the choice of events to be associated with integers. If a finite sequence of events is put into one-to-one correspondence with a set of real numbers ordered according to magnitude, then no objective features of the sequence will be changed if one chooses to put them into one-to-one correspondence with a set of successive integers, or indeed, with any set of real numbers ordered in the same way as the original set. There is, therefore, a kind of invariance under a generalized "change of scale" that is necessary to strain out another undesirable subjective feature. Actually, invariance under a continuous, one-to-one, order-preserving transformation must be admitted. Subjective time, in order to have an element taken out of it which has nothing to do with the world, must have its essential properties invariant under a group of continuous transformations which can be considered as generalizations of translations and changes of scale.

The discussion so far has really been little more than a consequence of the fact that Wiggy can acquire information about his world. We now assume that Wiggy interacts with the world and thereby acquires information about it. Suppose, for example, he slithers past a pebble and thus feels a sensation different from that of the ooze over a succession of tactile receptors. These sensations would successively constitute well-defined events in Wiggy's subjective time. Intrigued by the pebble, Wiggy can repeat his basic slithering operation, and realize that there is something repeatable "out there" with which he can interact and, as it were, thereby "punctuate" subjective time. He can interact with the "out there" in such a way that the earlier discussion of integers, interpolations, real numbers, etc. can be associated with the "out there". This isomorphic mapping is not an identity because Wiggy's subjective time is irreversible and can never repeat. But he can generate strings of sensations again and again which occur in one-to-one correspondence with intervals of subjective time. There is thus something "out there" which is at least complicated enough to contain something homeomorphic to one-dimensional continua bounded by two events in subjective time. Wiggy must thus live in a world which is at least $(1+1)$-dimensional. We say $(1+1)$ rather than 2 because of the fundamental subjective difference (reversible versus irreversible) between the two kinds of continua.

It is easy to show that the "out there" is complicated enough to contain a subset of dimensionality 2 rather than just 1 as demonstrated. Wiggy can perform operations, and is free to choose whether or not he does. As he slithers by his pebble, he realizes that he can vary his relation to it or avoid it altogether. He finds that even his approach and avoidance operation can be analyzed into a sequence of sensed events. The mere freedom of choice as to whether to interact or not implies that the "out there" must contain a "dimension" mappable into subjective time homeomorphically in the same way as the first one. We can thus say that Wiggy's world is at least $(1+2)$-dimensional. Without the element of free choice, which entails at least one new dimension, the concept of an experiment is vacuous; one would not need to invoke dimension beyond $(1+1)$. All three dimensions are homeomorphic to the real number continuum, and we are justified in requiring objectivity in the sense of invariance under the generalized translation of origin and change in scale discussed above for each "coordinate". Wiggy's "space-time", which is the direct product of his at-least-one-dimensional subjective time and his at-least-two-dimensional "out there", is thus a topological space admitting a transformation group corresponding in some way to a concept of objectivity.

This is not the place to go into the details of the theory of topological spaces, topological groups, or topologized algebraic fields. It is easy to show, however, that Wiggy's at-least-$(1+2)$-dimensional space-time admits the usual topology, is locally compact, is connected, and satisfies the second axiom of countability. The "translations" are isomorphic to the group of translations in a linear vector space; one can associate translations bi-uniquely with points of "space-time" (with some fixed choice of origin), and they have the same topology as "space-time". The generalized scale change goes over into a group of continuous transformation which satisfies the usual distributive law with respect to the translations. From this one can show that the objectivity transformations discussed earlier must form a topologized algebraic field which is locally compact and connected and which satisfies the second axiom of countability. It is known that any topologized algebraic field satisfying these conditions must be isomorphic to one of three such fields. These are the real numbers, the complex numbers, and the real quaternions. Also, the translation group has the same dimensionality as the full group. As Wiggy's space time, and ours, has been shown to be at least $(1+2)$-dimensional, the objectivity argument shows that his (and our) space-time is uniquely $(1+3)$-dimensional.

This is a very powerful result. In a sense, it is a prologue to relativity. Nothing has been said about equivalent observers; everything is in terms of a single observer. The objectivity condition is, in a sense, an antisolipsist condition. It is right and proper that a fundamental result like the dimensionality of space-time

Kodak reports on:

**how to cope with many, many, many oscillographs . . . KODAR—
a name with a ring to it . . . a motion picture to move bosses**

Feet, not inches

America's oscillographs are spewing out paper so fast that processing facilities are swamped.

To smash the bottleneck, we marketed last autumn what we called Kodak Ektaline Paper and Chemicals. Instant success.

We were a little crafty. We advertised 180 inches/min processing speed and hoped that would sound fast. (You can't hang us, since available oscillogram processors couldn't operate much faster.)

How primitive that figure looks, now that the last link of the Ektaline chain is in place!

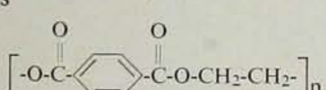
We hereby offer the new Kodak Ektaline 200 Processor that processes Kodak Ektaline 12, 16, or 18 Paper at 200 ft/min. (Feet, not inches!) With this machine in your darkroom, evaluation of a 475-foot roll of data can commence less than 3 minutes after the paper has been brought in from the oscillograph and placed on the supply spindle. You can operate the machine slower if you want to.

It stands 66 inches high by 31 inches wide by 52 inches long. Threading, cutoff, and winding are all automatic. The machine presents you with tight, evenly aligned rolls. Quality of the result meets our ridiculously high standards. We'll sell you the machine for $19,500. If people are standing around waiting for their data, you can't afford to go much longer without addressing an inquiry to Eastman Kodak Company, Professional Apparatus Division, Rochester 4, N. Y.

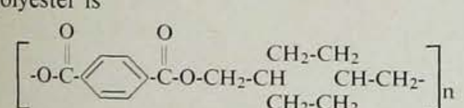
The improvement of capacitors

This is being written by a man wearing a suit and necktie of blended Kodel Polyester Fiber. Until we came out with "Kodel," the way to be chemically specific about polyester fiber, sheeting, and film without mentioning somebody's trademark was to say poly(ethylene terephthalate).

Whereas p(e t) is



Kodel polyester is



That large added ring preserves the bond between $-\overset{\text{O}}{\overset{\|}{\text{C}}}$ and O- against moisture attack and raises the melting point substantially to as high as 290C. Thence stem complex consequences that have encouraged us to bring into production a new plant at Orangeburg, N. Y. that puts it out as biaxially oriented Kodar plastic film.

You cannot take pictures on Kodar, but of the many other things you can do with it, one of the most impressive is to roll it up with metal foil into capacitors.

When the president of Kodak visited the laboratory where the many electrical advantages of Kodar were discovered, we set up ten .05-μfd 200-v capacitors for him, identical except that five of them had that cyclohexane ring in the polyester and five did not. We put them all in an oven at 185C and applied 700 volts of dc across them. Within three minutes all five of the p(e t)'s had shorted out. This was the logical moment for the president to leave, but realism is company policy. The president wanted to watch the first of ours fail. It took 10 minutes. With the relief of tension as soon as he left the room, we absently turned off the test. Statistically we calculate that the last of our five would have detained him 30 minutes. That was four years ago. Kodar dielectric film has continued to improve.

On March 26, 1959, having replaced 15 of the regular capacitors in a TV set with our kind, we set it to running 9 hours a day, 7 days a week. All other components that failed (naturally, there were many) we replaced. For the Electrical Insulation Show in February this year we removed the set from the room where the lab manager hides it and took it to Washington. It was the hit of the show. The coincidence that it happened to be the only TV set in the hall on the day when the first American was orbiting the earth might have helped focus attention on it. It would not have been a good place to have one of our capacitors go.

Back home in Tennessee we have a controller that we built to represent by capacitor charge the temperatures at 100 points in a chemical plant process. It senses rates and corrects accordingly. We couldn't find any other capacitors with sufficiently low leak rate, low dissipation factor, and constancy of capacitance with temperature, so we equipped the instrument with 200 Kodar film capacitors.

The prominent capacitor manufacturers know all about this.

Huntley with rope

We assume that the man in charge of photographic operations in a businesslike organization is not lazy and would rather see those operations expand than diminish.

We have made a 42-minute movie to stimulate his colleagues and his bosses to think up functions for him that might not have occurred to them.

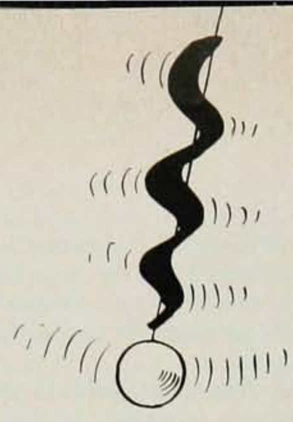
Mr. Chet Huntley narrates. We take you inside a cake being baked in Dayton. We puzzle you with a monstrous camera intended to take pictures in Cincinnati without perspective. We show you how they test a new hydrofoil on Lake Washington and what nooks and crannies a camera can explore when fitted with fiber optics. We take you to lots of places, starting on a classy note with the hunt for anti-matter at Brookhaven.

If we create the impression that the great linear accelerator there is nothing but another camera accessory, do not conclude that perspective is being shunned in Rochester as well as in Cincinnati. Historians of science differentiate between the "low technology" that civilizations evolve over the millenia for hewing the wood and drawing the water of everyday life and the "high technology" that is called into existence by the demands of pure science and then very kindly lowers a rope to haul up the "low technology." Maybe 1520 feet of movie film narrated by Mr. Chet Huntley with music and color to dispel boredom is better than rope.

To book a showing of "Photography at work . . . a progress report" write Eastman Kodak Company, Professional Photographic Sales Division, Rochester 4, N. Y.

Price subject to change without notice.

This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasionally a little revenue from those whose work has something to do with science



should be uniquely accessible to a single observer. If this were not the case, one would never have any basis for the concept of equivalent observers. There would simply be no assurance that the worlds of independent observers need have anything in common. Otherwise expressed, one can have no meaningful dialogue without a preceding meaningful monologue. Before one can have mutual consistency, one must have self-consistency.

Wiggleworm Physics

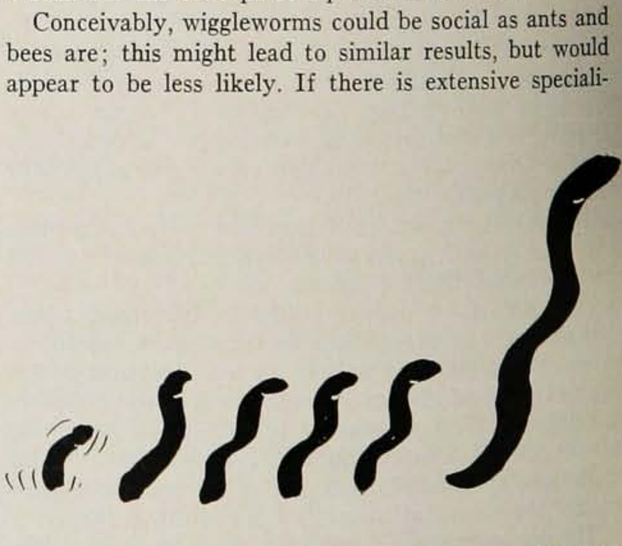
It is now clear that Wiggy can establish a metrizable (though not yet metric) space-time on the basis of operations he can perform. It is clear that for him topology is more apt to be considered elementary geometry than is the plane geometry taught in our high schools. The reason is that metric concepts are much less easily accessible to him than to us. Our skeletal system naturally conditions us to them (e.g., so many feet or so many paces). Primitive observation of astronomical phenomena and seasonal changes present an omnipresent stimulus capable of leading to a metric time concept. Observations of natural objects (rocks, mountains, trees, rivers, etc.) and their relations to subjective feelings of fatigue, corresponding to covering large distances, naturally lead to metric space concepts. Indeed, the existence of natural independent primitive space and time metrics has led historically to consideration of space and time as unrelated coordinates. It is essentially with the advent of relativity that their close connection was forced on physicists. In a sense then, Wiggy might have an advantage over us in that he would, from the beginning, be less apt to divorce the two.

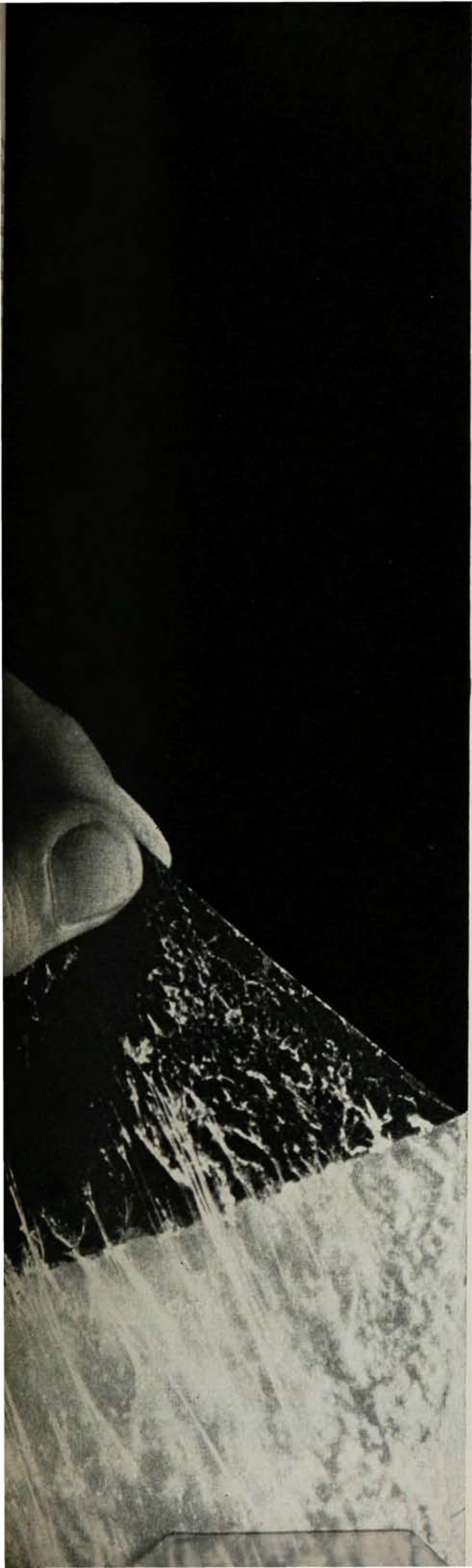
How could he develop metric space and time concepts? Galileo first discovered the isochronous property of the pendulum by timing the swings of the chandelier in the cathedral at Pisa against his own pulse. If Wiggy has a heart, he would be able to calibrate his subjective time with his own heart beats. More generally, he might use approximately cyclic variations in physiological needs or functions for the same purpose. His metric time concept could thus shift its basis from the informational (which, as we have seen, is nonmetrical in this context) to a thermodynamical basis in the sense that it depends on more or less uniform rate processes. As we have buried him in black ooze, astronomical phenomena are beyond his ken. Even the diurnal temperature variations connected with the solar day would not help him as he is well insulated from them. But from the cycle of life, growth, and death, assuming the wiggleworms have even the most rudimentary kind of social organization, some kind of time concept could develop in which time intervals would precede and succeed the life span of an individual wiggleworm. A kind of "public" time, in the sense of not being uniquely associated with a specific wiggleworm, could thus develop.

The social nature of public time is clear; it is tied up with the customary meaning of objectivity in physics. This concept is often formulated in terms of a transformation group on a set of equivalent observers; this much "relativity" is a feature even of Newtonian physics. The sense in which we used objectivity in the space-time discussion corresponded, in essence, to the assumption that an objective world existed about which a single observer could gain information. The kind of objectivity we are talking about now is, as it were, agreement between many such subjective observers about some features of the assumed objectively existing world. It would appear that this kind of objectivity (or "reality") represents the limit of concern of the scientist as scientist; carrying objectivity or reality further than this would seem to involve philosophy, mysticism, or theology. Wiggy would probably become as embroiled in the latter kinds of consideration as we have, but, as we are writing a Gedankswissenschaftsgeschichte for wiggleworms, we restrict the discussion to the scientific part alone.

This basically social aspect of science is extremely important. If wiggleworms were hermaphroditic and laid eggs which were abandoned as soon as they were laid, a wiggleworm society might never develop, and science would not develop beyond what a single wiggleworm could do in his lifetime. An excellent way to insure the possibility of social development would be for the wiggleworms to reproduce sexually and to have all the little Wiggies brought forth alive and dependent on their parents. In this case many forms of social contact would be unavoidable, and the mere facts of living would lead the wiggleworms to know that there were other wiggleworms like them and thus to provide a basis for the concept of equivalent observers.

Conceivably, wiggleworms could be social as ants and bees are; this might lead to similar results, but would appear to be less likely. If there is extensive speciali-





One of a series briefly describing GM's research in depth

Adhesion:
describing an elephant of science

Adhesion has certain similarities to the elephant the blind men were asked to describe. This interdisciplinary subject has occupied the talents of the physicist, chemist, mathematician, metallurgist, and polymer scientist. But still, what adhesion is—its mechanisms and principles—seems to have eluded an overall scientific theory. Perhaps not for long.

Food for inductive thought is being gathered from fundamental research studies around the world. At the General Motors Research Laboratories, for example, recer experimental work by our polymer scientists has supporte the idea that adhesion is dependent on:

(1) specific chemical groups in the adhesive film

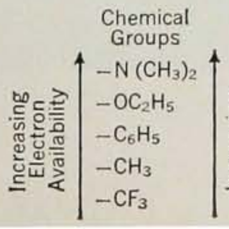
(2) surface roughness of the metal substrate to which the polymeric film adheres.

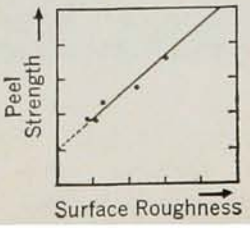
Particularly, through a range of polymers synthesized in t lab, they have found that the more available the electron in the chemical groups, the stronger the adhesion. Similarly, the rougher the metal surface, the more force required to break the adhesive bonds between the polyme coating and the substrate.

This experimental approach is enriching our understandin of some of the fundamentals affecting adhesion. It is also finding practical use in General Motors, helping in improving the adhesion of paint, rubber, plastics, and metals to each other. It's another example of GM's continual quest for—A BETTER WAY.

General Motors Research Laboratories

Warren, Michigan



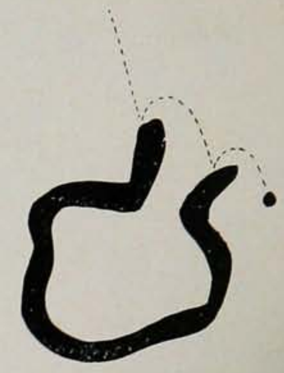


zation, large chunks of experience relevant to genesis of scientific concepts might be lacking for a particular individual. Among social insects the workers are divided into groups who ceaselessly work in narrowly circumscribed spheres of activity. It seems a bit harder for individuals with "tunnel vision" to develop scientific concepts than individuals without such blinders.

We must get back to the business at hand and leave the love life and social customs of the wiggleworms in abeyance, amusing as they might be. We assume that they communicate with each other, pass information from one generation to another, and that information storage is not limited by the memories of any fixed finite number of wiggleworms. Their language need not be phonetic—it might be tactile, chemical, or even electrical. Their "written" language might involve arrangements of pebbles, solidified secretions, or tastable compounds of one sort or another. The particular media used for information storage are not significant here, likewise the sensory modes used. The communication channels will, of course, utilize sensory channels, and in particular, those channels by which information is obtained about the world. This may well be what makes language possible in the first place, for words are, to a large extent, encapsulations of experience. They have semantic content in mediating communication between individuals to the extent that they draw on common experience. One might even argue that the world exists objectively because we can talk about and concur in our descriptions of aspects of it! The development of language thus appears to be essentially the first phase of the development of science either for Wiggy or for us.

Wiggy will sooner or later discover pebbles, bones, shells or similar objects in the muck. Manipulating a pebble is an experience that can be shared by many wiggleworms, so primitive concepts of rigidity and ooziness can soon become public. We assume that gravitation operates in Wiggy's world; even if he is neutrally buoyant in his oozy medium, he can discover that it is easier to move a pebble to one side than to raise it, or that a raised pebble settles back in place. He can thus generate primitive concepts of force and work, which can be encapsulated in the public language. From pebbles he can develop the concept of a rigid body and convert his topological space into a metric space.

Exertions in pushing pebbles about and slithering past them could lead to concepts of velocity and acceleration, and of inertia (mass), and could also lead to a kind of clock. Wiggy could, for example, push one pebble on top of another, the lower pebble resting on a shell. The time of settling of the upper pebble from the time his tail knocks it off until his head senses its impact with the shell might well be a fairly reproducible interval. Ultimately, of course, standard pebbles and shells and precise instructions for their use would be preserved in the Wiggleworm Bureau of Standards. It might take a long time until all the inconsistencies between one set of pebbles and the next could be worked out, or even for one set to be used consistently. It would probably take even longer before the chemical rate processes Wiggy can sense could be clocked in an objectively reproducible manner.* But though the way might be arduous, there is little doubt that a wiggleworm genius could go a long way just with his own arbitrary set of standard pebbles.



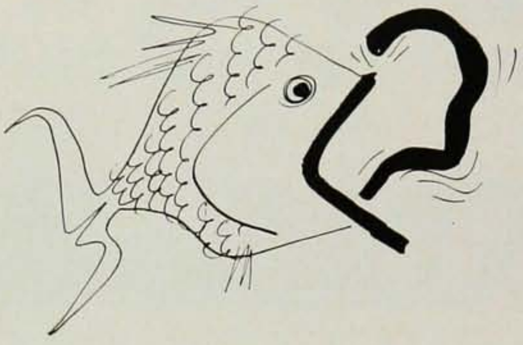
It might be hard for Wiggy to arrive at Newton's laws because falling objects would probably reach terminal velocity in less than a flip of his tail. However, the shells would themselves be able to be tipped and manipulated so that he would be able to discover things about acceleration by slowing things up the way Galileo did with an inclined plane. Indeed, he might even discover the isochronous properties of the small oscillations of a pebble sitting in a concave shell. Ultimately, Wiggy might discover that he could have a pebble in a shell, with another shell over it, and exhaust the ooze from the neighborhood of the pebble. He could then get a pretty good pendulum; the wiggleworm who first discovered this would no doubt get the vermine equivalent of a Nobel prize. The wiggleworm who found a nicely spherical pearl and applied it to the clock problem would probably get a prize, too.

Armed with a metric space and time, Wiggy can now turn back to chemical rate processes, using his chemical senses to measure the extent to which the reaction has occurred. He will note the speeding up of chemical reactions with increasing temperature. He can do this because processes of fermentation, decay, or the like are often exothermic. It is probable that his initial temperature concept will be less one of equilibrium than one having to do with rates of chemical reactions.

Many chemical reactions produce gases. Sooner or later Wiggy may find a gas bubble trapped under a shell. He will then realize there is more to his physical universe than wiggleworms, enemies, food, ooze, water, and hard objects. He will learn that these bubbles have paradoxical properties; they fly up instead of falling down. Eventually some bold wiggleworm "astronaut" may emerge into the water from the safety of the ooze, his "spaceship" a shell using a gas bubble to attain close to neutral buoyancy.

* Rather accurate biological clocks exist, but they all seem to require a light flash to set them going, we have denied Wiggy even a single light flash.

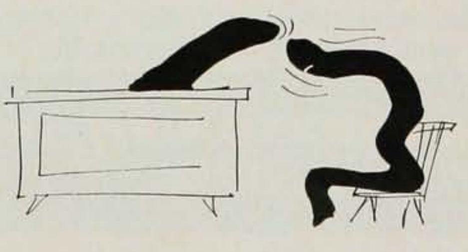
We have no time here to recount the role of the numberless wiggleworm heroes giving their lives for the exploration of the unknown and the advancement of science, braving predatory monsters in the sea above, armed with no weapons: blind, helpless, tasty morsels.



But the dauntless spirit of the wiggleworm ultimately triumphs over these obstacles. In every generation some intrepid hero braves the unknown until at last one makes a safe return. Wiggy then realizes that above his dark, resisting ooze there is a new world whose substance penetrates his own (and of which he can safely get little samples between two shells by a laborious mud-siphoning technique)—and full of horrible monsters.

We rapidly pass over the heroic age of navigation and exploration during which the search is on for suitable shells and possibly during which techniques are developed for making artificial shells in the sense of navigable protective containers. We can envisage Wiggy's technology developing and his civilization spreading out as his fellow explorers colonize distant ooze patches and perhaps even subjugate other wiggleworms. One can imagine the gradual domestication of other forms of sea life; this is, after all, but a kind of intelligence-directed symbiosis. It is even possible that Wiggy could learn much about the sea, sitting securely in a domesticated sea anemone. He might even sail safely in a "warship" festooned with the stinging tentacles of domesticated sea animals.

The technical conquest of the clear-water environment would generate tremendous stimuli for all branches of wiggleworm research. The details of how different wiggleworm communities would vie with one another in supporting hydrospace research in the interests of national defense must be omitted in this brief account, as we are dealing with scientific, rather than military or social history. Suffice it to say, however, that the great breakthrough into the hydrosphere led almost immediately to clearer understanding of the laws of fluid mechanics, mechanics generally, to the discovery of heat-generating radiation coming in from above, with its definite cycles of waxing and waning, and to biological information of an often unpleasant nature.

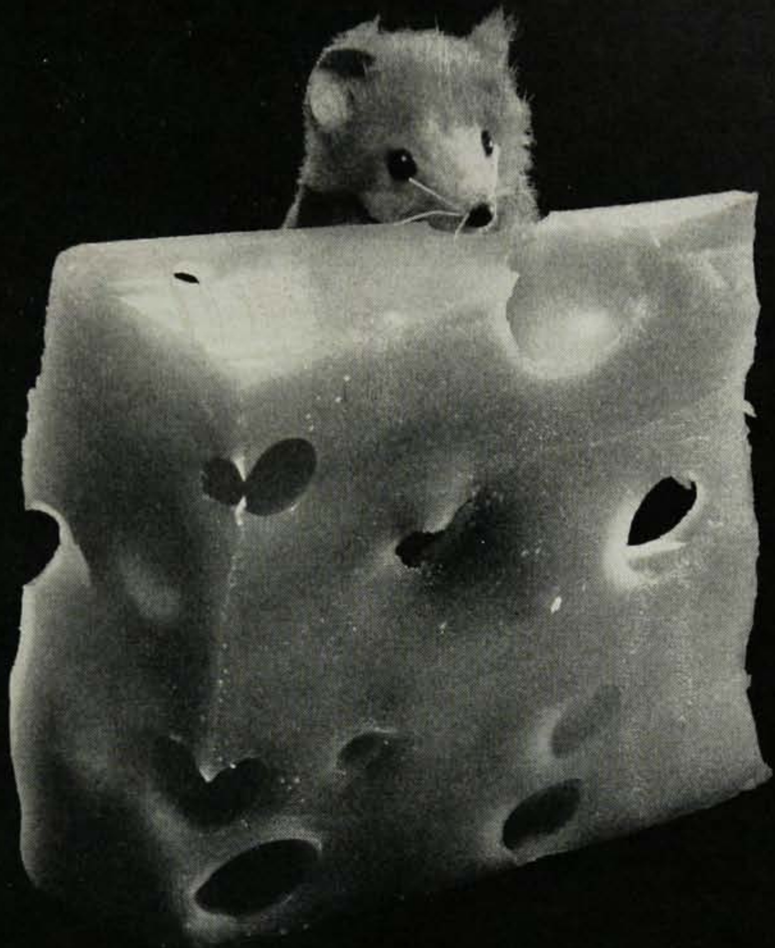


The first contacts with light would leave a tremendous impression on the history of wiggleworm science. It could feed back into his time and temperature measurements, because now all the ingredients for forming the concept of a solar day and a working model of a gas thermometer would now be at hand. Wiggy could use the latter to get to a forerunner of the thermodynamic temperature scale.

One would expect chemistry and thermodynamics to develop rather early; astronomy, along with many other sciences whose beginnings are primarily visual or mechanical, would develop much later. One would expect to find organic chemistry racing far ahead of inorganic chemistry. Indeed, many fields historically associated by us with metallurgy, inorganic chemistry, or physics, would have their origins in complexities of organic chemistry accessible to Wiggy. Most of his knowledge of radiation physics would probably come from the interaction of light and complex organic molecules. Light would probably be discovered in the first place by its heating effects (via the absorption bands of organic pigments); this was how we discovered the infrared region of the spectrum. Photovoltaic effects could give rise to the first electric cells, though it is possible that organic oxidation-reduction reactions could be earlier observed to produce similar results. Electric currents themselves would probably be first sensed either physiologically by direct contact, or by chemical senses responding to local changes in *p*H. Organic conductors and semiconductors would probably be highly developed before the discovery of metallic conductivity. Metals would probably be first produced electrolytically. Electrolytic production of hydrogen and oxygen would undoubtedly be an important technical means for producing buoyancy in vessels used to navigate in the waters above.

The foregoing possibilities are just a few of the directions wiggleworm research might take; clearly, the particular course of events would be strongly influenced by accidents. As with us, serendipity would be an important and frequent factor in progress. Because Wiggy is so handicapped compared to us, it might be much more difficult for him to get started than it is for us. But once he is on his way, one can see that the process of acquiring knowledge about the universe will be self-catalytic in the sense that every advance tremendously facilitates further advances.

It hardly seems necessary to carry our fairy tale much further. We can leave it as an exercise for the reader to discover how Wiggy might finally discover the sun and stars, or how he might eventually be able to explore the land. The latter would be as hazardous and difficult an undertaking for him as exploring a distant planet might be for us. Discovering the facts of meteorology, geology, the solar system, our galaxy, and



What is the moon made of?

No. Guess again.

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some of the large-scale structure of the universe, would surely represent a combination of exploration and intellectual pioneering at least as great as anything we have yet done. The lesson to be drawn from these considerations, however, is that there is no reason in principle for believing that he could not ultimately do all these things and more.

Human and Vermine Theories

Einstein and many others have stressed the fact that advances in theoretical physics represent far more than the gathering of data. There must be free play of the imagination and intellect, and a striving to order the raw facts of experience. It seems clear that Wiggy would have to think much harder about the facts of his experience than we have had to. Indeed, if he were only as smart as we are, one might be quite skeptical about his being able to get very far even in ten million years, say. But if the average wiggleworm has the curiosity, drive, and imagination of our great scientists and explorers, and feels the same need to order his experience that we do, then it seems likely that they could do all the things discussed above in a time scale short compared to the time life has been on the earth.

At any one time, wiggleworm science would probably not bear a close resemblance to our own. His notions of energy, for example, might arise from chemical thermodynamics rather than from mechanics. Energy might have "dimensions", not of mass, length, and time, but perhaps of force, volume, and temperature. What meaning, then, can one ascribe to the question as to whether Wiggy and we can come up with equivalent pictures of the universe?

Before this question is answered, we must realize that our picture of the universe is constantly changing. The picture at any time has evolved from earlier pictures. It agrees with older pictures within their areas of satisfactory applicability, and also affords a convenient encapsulation of experience in some areas where the old pictures are deficient. Wiggy's pictures would evolve in the same way. We can assume that he has similar criteria to ours for the validation and improvement of his theories, namely that they agree with experience, and be as simple and convenient (and maybe as elegant) as possible. It seems improbable that one of our pictures would ever completely coincide with one of Wiggy's even to the extent of isomorphism (two theories, T_1 and T_2, are isomorphic if any consequence of T_1 can be deduced from T_2 and any consequence of T_2 can be deduced from T_1).

This does not mean that Wiggy and we would never be able to agree on what the universe is like. What it does imply (given that whatever Wiggy meets in his exploration of the universe would ultimately be encountered by us as we continue our research and exploration, and that he is ultimately confronted with any phenomena we observe) is that a relation between the two expanding sequences of pictures can exist which we can call dynamic homomorphism.

To introduce this idea, consider a sequence of pictures of the world which we have created: $H_1, H_2, \ldots H_n \ldots$. Let the subscripts number the pictures such that the higher subscripts correspond to later, more inclusive theories. If $i < j$, we write $H_i < H_j$, where the inequality signs means that H_i covers a smaller body of experience than H_j, and that in that portion of experience where H_i holds with reasonable accuracy, it is an approximation to H_j, with the description afforded by H_j at least as good as that afforded by H_i. In a similar fashion, we consider a sequence of pictures that Wiggy establishes, designated by $W_1, W_2, \ldots W_m \ldots$. The same conventions with regard to the subscripts and the relations between W_i and W_j are assumed to hold as discussed above for H_i and H_j. As the construction of pictures is an open-ended activity, there are no finite limits on how large a subscript is admitted either for Wiggy or for us. Furthermore, and this is the scientist's act of faith, we assume that any operationally accessible aspect of the universe must be encompassed in some H_n or W_m, providing n and m are large enough.

We can now explain dynamic homomorphism. By this we mean that given any W_p, there will exist an H_q, where q depends on p, and such that $W_p < H_q$. Also, given an H_r, there will exist a W_s, where s depends on r, such that $H_r < W_s$. In effect, we can view the two sequences as bearing a rough analogy to two distinct dissections of a straight line into intervals of finite length. Perhaps an even better analogy might be two distinct dissections of some complex measure space into sets of finite measure (cells). In both cases one would start from an "origin", and the various pictures would correspond to the increasingly large set of points which contains the origin and which is successively augmented by the addition of contiguous sets.

Expressed in this form, it would appear that dynamic homomorphism applies to independent developments in human science, and basically no more or less than it applies to Wiggy's and our developments. Dynamic isomorphism (i.e., the existence of some t such that W_t is isomorphic to H_t) might never occur unless Wiggy and we compare notes.

It seems reasonable to conclude that though we shall always make errors or be mistaken to some extent in our ideas of the universe, we shall improve or correct our pictures sooner or later, and the same applies to Wiggy. Ultimately, when both he and we have covered the same accessible portions of the universe, we should find that the differences between our pictures would be only those of isomorphism. There seems to be no reason to believe, if an objectively "real" world exists, that Wiggy and we would end up with nonisomorphic pictures of the same body of experience.