

$1 + 1 \neq 2$ (One Plus One Does Not Equal Two)

PAUL WEISS

IN SCHOOL we learned that one apple plus one apple makes two apples. One apple and one pear is just one apple and one pear. If we choose to ignore "appleness" and "pear-ness," being concerned only with weights and numbers, as, for instance, in counting and weighing parcels for postal shipment, apples and pears would, of course, be reduced to just so many items, to be tallied by sheer summation. In equating such items, we gain as well as lose. We gain an easy way of measurement, but lose what nowadays would be called "information content." Apples and pears do not become alike; we simply discount their differences for a particular purpose.

But can we ever retrieve information about distinctive features once we have tossed it out? If not, can science, as man's striving for as complete and rational a picture of the universe as is obtainable to him by observation, experiment, and logic, stoop to trading loss of information content for the simplicity, convenience and, yes, true elegance, of blotting out distinctiveness based on disparity; for instance, between pears and apples? In fact, in nature, even two apples cannot be equated, if one lies rotting on the ground while the other, still growing, hangs on the tree.

In short, all algebra applied to nature implies abstraction. Sheer adding up always leaves out some relevant information. Whether such omission is passable depends on our purpose, and that, in turn, depends entirely upon our special interest. And since interest, by definition, connotes biased self-limitation, the information thus gained remains incomplete, short of the comprehensiveness to which science in its professed universality aspires. So, how sure can we be that sheer analysis alone—the physical or mental dissolution of a complex into a shambles of measurable but disconnected units—does not irretrievably destroy highly relevant data about nature? Is Phoenix, rising from its ashes, a true image of nature or just a myth?

In our day, the answers to such questions have become a matter of faith. The success story of learning more and more about less and less, which in the present context means about ever smaller fragments of nature, has grooved our faith in nature as an assembly plant of microevents. No doubt faith in the omnipotence of analytical decomposition has opened the mainsprings for the stream of

scientific progress. What we are apt to overlook in our enthusiasm is that there are other sources which could powerfully augment that stream were they not left to dissipate and dry up for doctrinary reasons. Doctrine has barred them from joining the mainstream by artificially erected walls, by conceptual injunctions against admixtures from sources suspected as contaminated because they failed to pass the orthodox test of purity, namely, that *one plus one* must be made to equal *two*.

The unorthodox dissenters usually phrased their argument in the age-old adage that "the whole is *more* than the sum of its parts." Look at this phrasing and you will discover the root of the distrust, and indeed, outright rejection, of the valid principle behind it. What did they mean by stating that "an organism is *more* than the sum of its cells and humors"; that "a cell is *more* than its content of molecules"; that "brain function is *more* than the aggregate of activities of its constituent neurons"; and so on? As the term "more" unquestionably connotes some tangible addition, an algebraic plus, one naturally had to ask: "More of what? Dimensions, mass, electric charges?" Surely none of those. Then what? Perhaps something unfathomable, weightless, chargeless, nonmaterial? All sorts of agents have indeed been invoked in that capacity—entelechy, *élan vital*, formative drive, vital principle—all idle words, unpalatable to most scientists for being just fancy names for an unknown X.

Unfortunately, in their aversion to the supernatural, the scientific purists poured out the baby with the intellectually soiled bath water by repudiating the very aspects of wholeness in nature that had conjured up those cover terms for ignorance. And as a prophylactic against their resurgence, they fostered a militantly doctrinaire "reductionism," which axiomatically prescribed that all the relevant macroinformation about nature must, and eventually will, be derived completely from adding up and piecing together the microinformations about the smallest sample units. Never mind that physics had to give up that claim gradually as Boltzmann's thermodynamics, Planck's quantum theory, and Heisenberg's uncertainty principle came on the scene. The life sciences have failed to follow suit and break out of the strait jacket of a doctrine for which their own subject matter furnished the most telling disproof. They might have come around more readily, though, if they had realized that systems with aspects of wholeness are by no means confined to living nature, but

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are of universal occurrence. In fact, their very universality should clear them of the stigma of vitalism.

Let me take a further step toward destigmatization by pointing to a veiled source of confusion that seems to have confounded past dealings with the problem—the failure to distinguish between a natural phenomenon as such and the symbols of language we have to use in order to describe it. A phenomenon to which we ascribe wholeness is certainly not *more* in algebraic terms than the sum of elementary phenomena composing it. It just is *different*. The difference is that between matter and structure. If there is a “more” involved, it lies in the terms of our description. It is we who, as describers, feel compelled to add extra terms of information for the sake of making the description of the integral phenomenon complete and pertinent.

This neutral and philosophically noncommittal characterization of the problem tries to allay, or if you prefer, circumvent, the present warfare of dogmas. It should soothe the apprehensions of those who have built faith in absolute reductionism as bulwark against onslaughts on their sense of intellectual security, and it should assure those others who felt disenfranchised because of their holist faith, their day in court. There is a current fad to present the subject matter of the life sciences in terms of a dogmatic schism—an antithesis of “molecular” and “organismic” biology, professing a reductionist and a holistic philosophy, respectively. The former is respected for its “rugged naturalism,” the latter suspected of flirting romantically with the supernatural. What I shall try to show is that exclusive commitment to either thesis is unnatural. The molecular and the organismic are but two different vantage points from which to look at living systems,

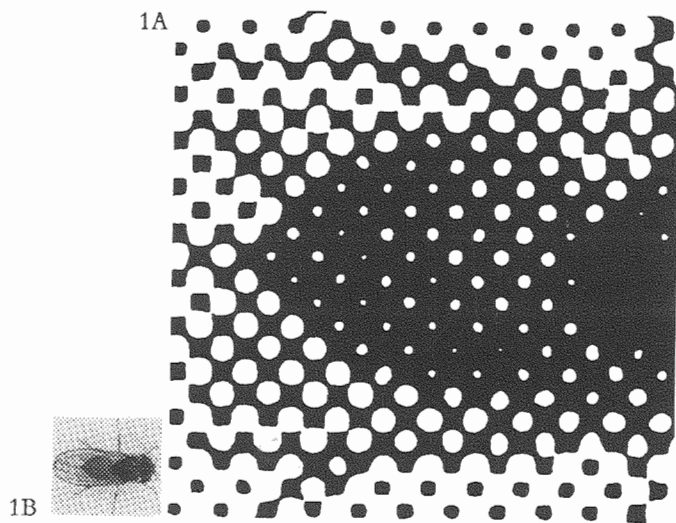
neither of them granting a monopoly to insight. They are complementary and co-equal. To document this proposition is the main object of the following discourse; I hope that it will serve as an object lesson.

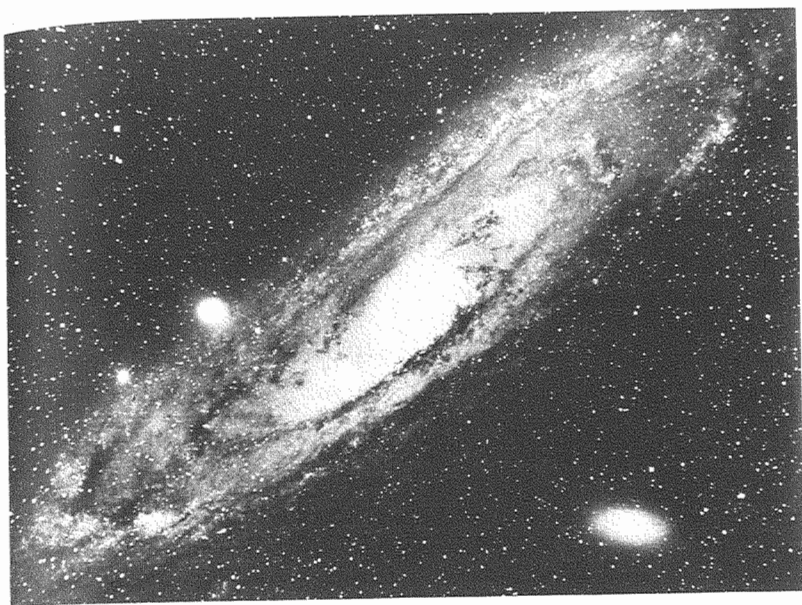
Specifically, these are the points I aim to prove: (1) that as our brain scans features of the universe we shift range and focus back and forth between telescopic and microscopic vision, as it were; (2) that as we move downward on this scale, we mostly gain precision and lose perspective; (3) that as we move upward, new and relevant features, formerly unrecognizable and unsuspected, come into view; (4) that this emerging novelty pertains to macro-samples of nature—that is, that it reflects properties of *collectives*—of groups, assemblies, systems, and populations, composed of microsamples; and (5) that the required additional terms to characterize such collectives must come from rigorous scientific procedure rather than from anthropomorphic translocations and allegorical allusions to mythology.

And now I turn from these somewhat pedantic generalities, which to some presumably will seem commonplace, to practical examples by which the validity of those five points can be tested. A brief glossary of our terms of reference may serve as introduction. Let us ask first: Of what do we deprive a system when we dismember it and isolate its component parts, whether bodily or just in our mind? Plainly, of the *interrelations* that had existed among the parts while they were still united. So, in trying to reconstruct the system from the fragments, whether bodily like Humpty-Dumpty, or symbolically in our imagination, we must make up for the deprivation by adding a proper term that specifies the lost relations. This may simply amount to adding vectors to algebraic terms. The requirements for added specifications will vary with the different degrees of order emerging from the union (or reunion) of elements combined in groups. The simplest case involves only a loose and widely variable relation, such as “togetherness”; it displays novelty, but little order. If, besides novelty, the collective shows regularities of pattern which recur with a high degree of invariance, we confer upon it the designation “organized.”

But here again we would do well to make a further distinction between true and merely simulated organization. We must distinguish between the genuine order, such as emerges within a group by virtue of its intrinsic dynamics, and a mere semblance of order, such as an aggregate of unrelated units acquires by imposition or imputation from without. Examples of the latter are puppets, or the proverbial camel our fantasy projects into a cloud, or, in fact, any effigy of a natural system, as in the following instance.

Figure 1 shows a meaningless array of dots in inert co-existence, with nothing recognizably in common besides

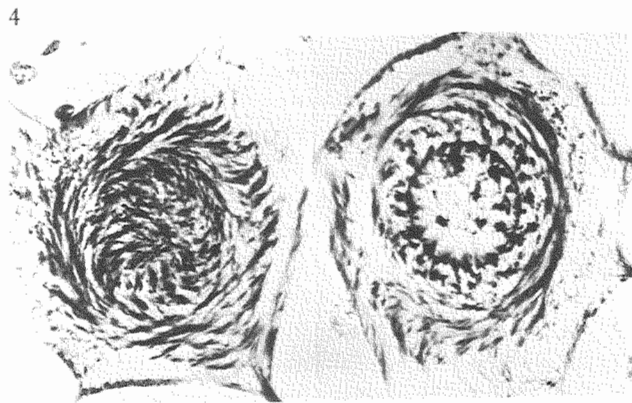




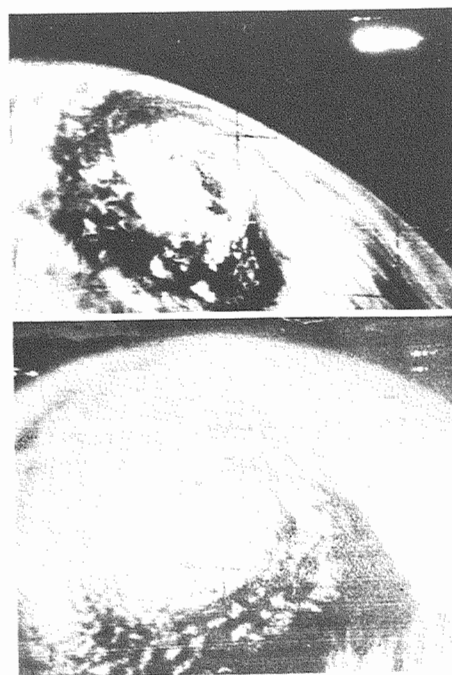
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the paper they were printed on. Yet, from a greater distance or, what is the same, at lower magnification (inset), we recognize them as the component bits of information about a continuous, well-structured image. That image, of course, is dead; the dots of printer's ink composing it are physically as unrelated as fly specks. What gives the picture its meaningful integration, are we, the viewers, with our eyes and brain. The dots do not "add up." We add to them. From this we learn that discontinuous and discrete elements can give us the illusion of continuity, but that the mere aspect of continuity alone is no test of inner coherence. Let me pursue this further.

Figure 2 is a picture of the spiral galaxy, Andromeda. Now, if you ask what Andromeda consists of, a census taker would reply, "So-and-so many stars"; a chemist might come forth with spectroscopically discernible distinctions. But would either of these answers add up to a



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definition of a spiral pattern? Certainly not. Nor would a scientist be happy if the additional feature were taken care of by invoking the magic act of "a spiralizer."

Closer to earth, Figure 3 shows photographs taken by the first weather satellite, Tyros. Note the cyclonic cloud pattern. But what are clouds in analytic view? Droplets of water. Now, could knowing all there is to be known about H_2O ever add up to a picture of this configuration? Of course not: the winds that have shaped it remain invisible. In Christina Rossetti's words,

"Who has seen the wind? Neither you nor I.
But when the trees bow down their heads,
the wind is passing by."

So, here we meet the first caveat against willful isolation of an object from its natural context.

More spirals next, in Figure 4: the neurofibrils in the large motor cells innervating the electric organ of the torpedo fish. To say that these fibrils are made of protein will neither describe nor explain their spiral course. Indeed, from what we now know about their formation, the picture is just a photographic still, a momentary sample of a continuously unwinding record of motion in that cell. These spirals are but the residual traces of a moving stream of substance, the pattern of which must be sought in regularities of the underlying dynamics.

Here lies a general and basic lesson. What we perceive as static form is but the product, transitory or lasting, of formative *processes*. The features of the product—for instance, its geometry—can provide us with clues for the dynamics that underlie those processes. For instance, the counter-

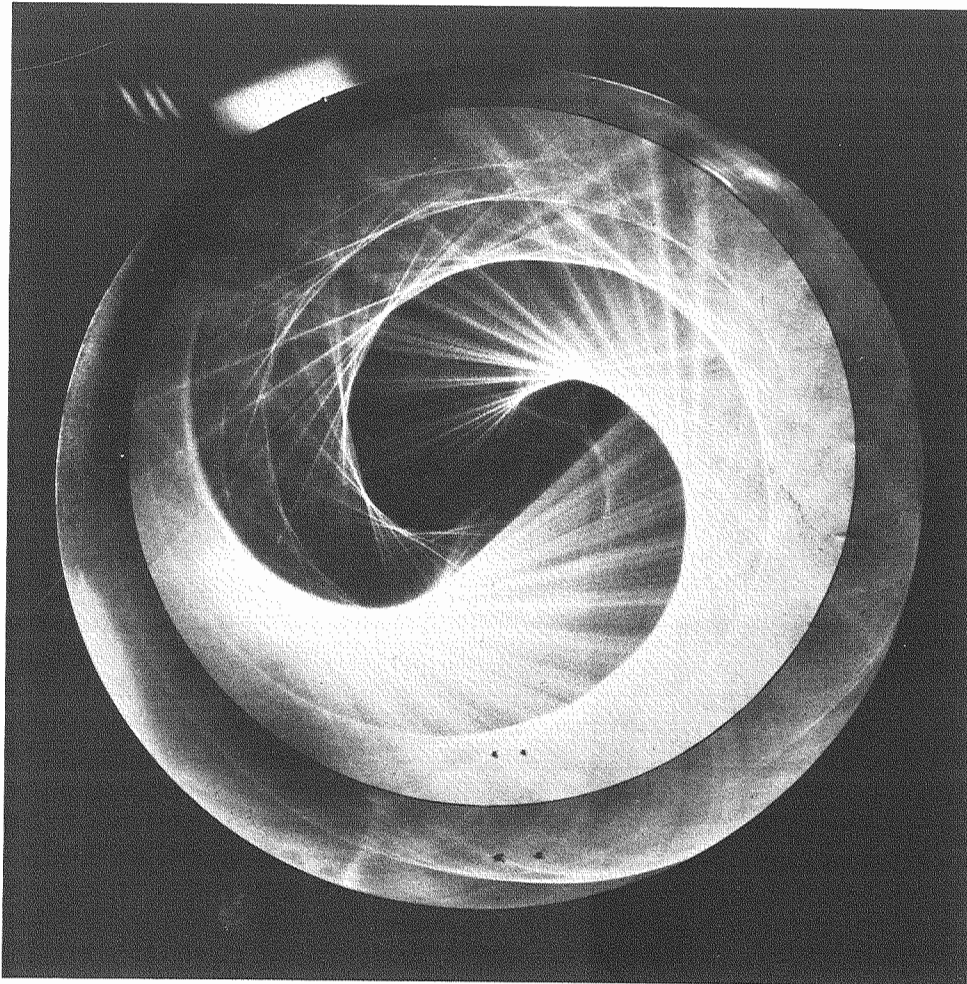


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clockwise spiral spin of water running off a bathtub drain is but an indicator of an asymmetry of forces resulting from the earth's rotation. The order we perceive in structured form thus is not primary, but the expression of the dynamic patterns that have engendered it. Yet this is only a beginning. Through their results, dynamics modify the setting for subsequent dynamics. Dynamically created forms, if somehow consolidated, become molds for the course of further activity. Free-flowing water grooves its bed until the bed begins to channel further flow, as in this instance (Figure 5) of a spiral spout carved by the twisted course of water that drained from a glacier bottom in the glacial age. Once formed, the spiral structure becomes self-perpetuating, gaining in polish and perfection by more erosion.

In passing, let me point out that by this dual action, a whorl can serve as a general model of how dynamic patterns tend not only to preserve, but in further consequence

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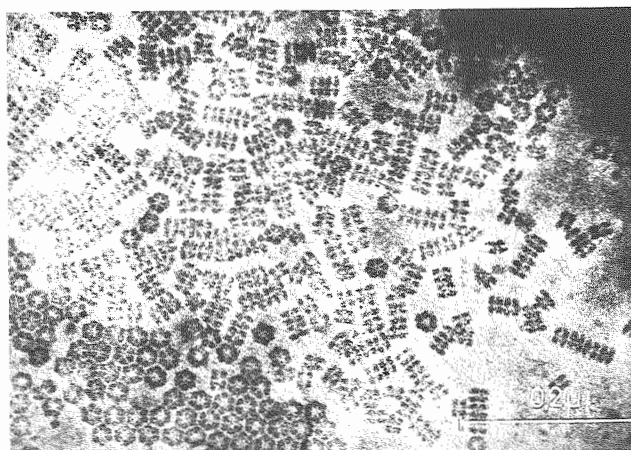


to accentuate, their self-engendered structures. I wish to stress this because of the obvious bearing the general two-step principle has on our understanding of brain mechanisms: of grooving, habit formation, facilitation, and learning theory. If taken seriously and followed up, it might dispose of the necessity of placing rigid fixation and plasticity of neural functions—instincts versus memory—into sharply divided categories, each run on a different principle.

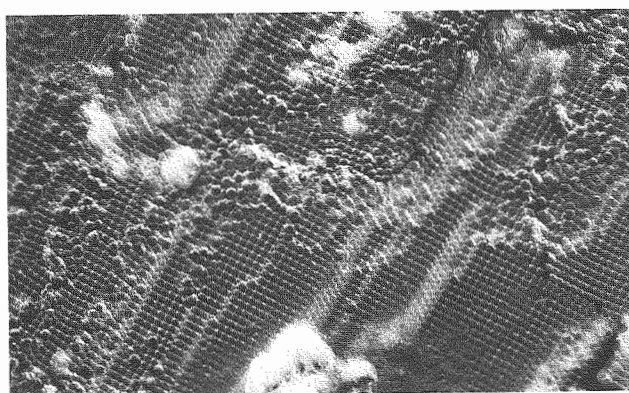
Returning to our main line, we have recognized the spiral wall of the glacial mill as the dead effigy of the unitary dynamic sweep pattern that has created it. The spiral composition of an artist (Figure 6) is, similarly, the projection on dead canvas of some dynamic process, obeying mathematical terms for spirality, that has been going on in the artist's creative brain. Attempts to resolve this act to mere terms of numerical plurality, whether of neurons or of intraneuronal molecules, would seem to me to be as futile as to derive the spirality of a spiral nebula from our knowledge of single isolated stars.

By now I have exposed three propositions. First, that collectives tend to display novel features not discernible in their component units, hence justly called "emergent"; second, that such features are indicative of the existence of significant *relationships* among the members of the collective, such relationships being severed by physical or mental separation of the members from each other; and, third, that whenever one is faced with static geometric regularities of patterns, he ought to look beyond them—or, rather, behind them—for the rules in the play of forces that have shaped them. In thus raising the sights from statics to dynamics, static *interrelations* become dynamic *interactions*, and in the case of self-sustaining systems with the conservative features of wholeness, simple *interactions* become *interdependencies*. *States* then appear as but cross-sections through trains of *behavior* along the time-line, *scalar* values must be supplemented by *vectorial* interconnections, and vector systems of specifiable integral properties become realities. Let us then keep in mind that this progression from *elements* to *groups* objectively reflects the ascending scale of supplemental statements we need for adequate description of corresponding objects of our experience. I shall then present samples of such phenomena in that order. By choosing them from various points along that scale, I intend to blur the artificial dichotomy between modes of thought centered either on *elements* or on *continua*, each to the exclusion or invalidation of the other.

I shall use the example of *form* as master indicator of order. Its simplest examples are plain aggregates of identical units stacking up flank-to-flank or end-to-end, according to steric fitting, like key to lock, and chemical conformances. The macromolecular units of the blood pig-



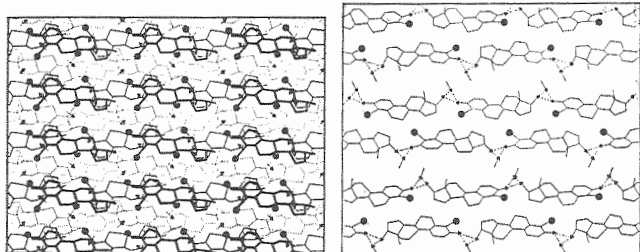
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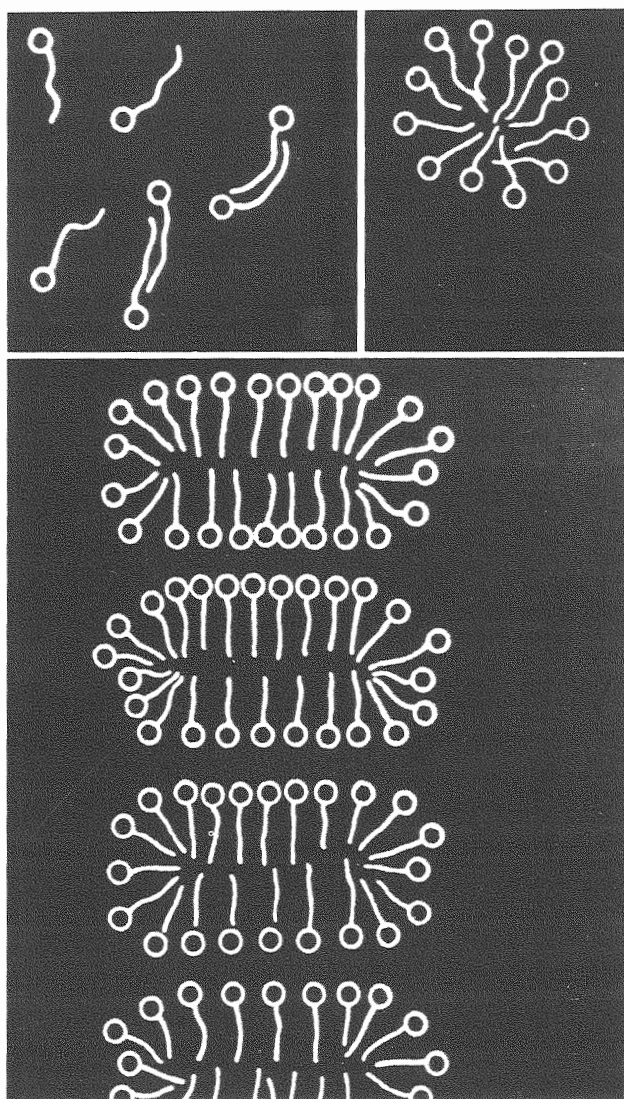
ment of a marine worm (Figure 7), each consisting of six subunits around a hole, stack up in contact: molecules as "modules." The only novelty by which the group differs from a mere sum of units is its predominantly planar array—a significant, yet low, degree of order. The stacking of virus particles (Figure 8), in its near-crystalline configuration, falls in the same class, although the forces interlinking the units so regularly are not equally obvious.

A polymer, as I shall show later, is a linear chain of identical links with couplings, end-to-end, like a railroad train. The linkage represents a first step of order in the assembly. The straightening of the chain from random coils to rectilinearity requires an additional step of ordering. For short lengths, intermolecular forces may serve as an explanation, but ruler-straight arrays over great distances undoubtedly must be referred to straightening effects from the environment; for instance, stretch. Common direction may be imposed by a further polarizing interaction with the environment. And so, in order to describe the formation of, for instance, a connective tissue fiber, we must construct steps of ever more specifications.



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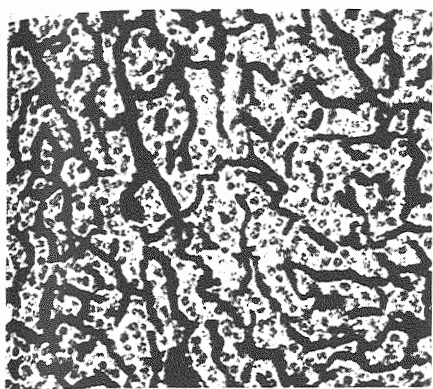
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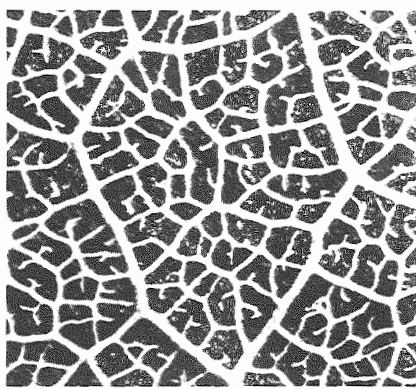
The stacking of lipid molecules into lamellar systems of the so-called *smectic* state (Figure 9) extends the same principle to *two* dimensions. Here, too, the environment enters as an ordering factor in that it offers to the molecules, as scaffolding for their own planar self-array, a planar interface between two immiscible media. Lacking such guidance, the molecules cluster into so-called *micelles* (Figure 10), yet by no means as random conglomerations, but in orderly structural patterns determined by their own collective interactions. For each of them the others are part of its environment—a forward reference to our conclusion that the notion of independent “elements” is, in itself, an abstraction, for in reality elements are part and parcel of a single, undivided continuum that embraces units and environment as one integral entity.

Yet, clearly, structural group order in these past examples can still be satisfactorily explained in essence by the microprecise automatic assembly of individual units and subunits, united like an erector set by their steric, chemical, and electrical properties. Such rigid compounding processes can hardly serve as star witnesses in our suit for a divorce from the one-plus-one-equals-two precept of thought. Therefore, let me proceed to a series of further samples, representative of higher-order systems. These are collectives of the following description: their features, “on the whole,” show well-defined *regularities* of pattern, recurring consistently from specimen to specimen in each given class; but as one looks at smaller and smaller samples, similitude and regularity decline until, having descended to the elements, one can no longer find any hint of what the structure of the total complex might be like. This is because the *details* of pattern are in each case *unique*, no two microsamples being ever alike, even though the *composite pattern of the whole*, case after case, is of the same standard form. Contrary to the preceding examples, the order of the whole can here no longer be predicted from a simple upward projection of the elemental properties of single units stacked up in module fashion. The following illustrations will make this more specific.

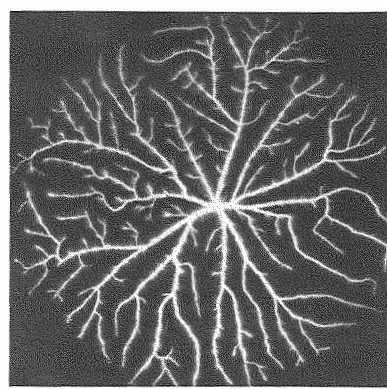
Take, for instance, the bed of blood capillaries in a tissue (Figure 11). They branch and re-anastomose almost at random, yet the resultant network offers an aspect of great over-all regularity. Descriptively, the regularity is reflected in the near-constancy of distances between the branches; dynamically, it reflects a growth pattern elaborated by interactions of the component branches, both among one another and with the cellulated matrix they pervade. In oversimplified terms, the interactions involved are a type of *competition*. This, then, is interaction no longer in contiguity, but at a distance. Each branch may be viewed as surrounded by a shell of influences of graded strengths—*domains*, which keep each other at a re-



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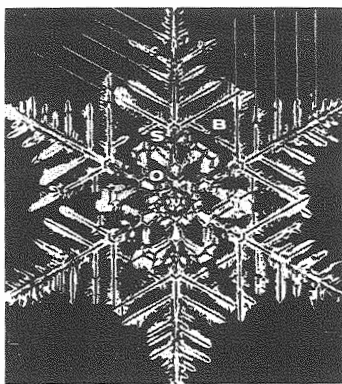
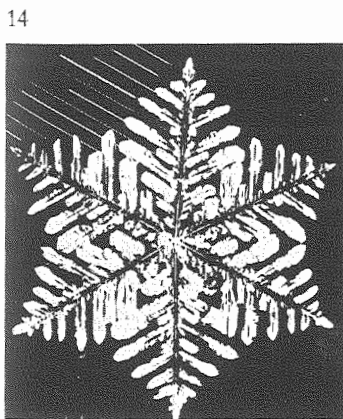
spectful standard distance. The term “domain” is used in forward reference to subsequent comments on field and gradient principles.

A botanical counterpart to the capillary bed is the venation of a leaf (Figure 12). But let me at once dispel the notion that growth patterns of this type are a preserve of organisms. The next picture (Figure 13), for instance, shows the lightninglike pattern of an electrostatic discharge from a point source. Ideally, it should, of course, be radial but in reality, the unpredictable variations of conductance and resistance, resulting from the random inhomogeneities of the medium through which it has to travel, establish spearheads for separate and competing ionization tracks. Despite this capriciousness in detail, the total picture still emerges as one of systemic order. Growth patterns of snowflakes (Figure 14) also show infinite variation of detail within a high degree of constancy of the over-all form of the growing crystal.

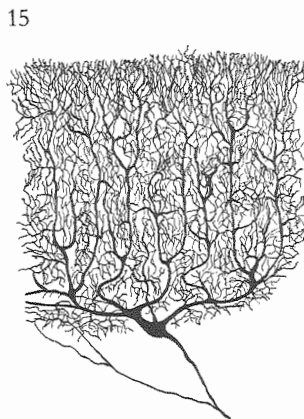
The growth pattern of a nerve cell from the cerebellum (Figure 15) reveals the same rule: the same degree of un-

predictability of the details of ramification, yet at the ends great uniformity of distribution among the terminal branchlets. While it is their environment—the matrix of the brain—that offers to the advancing branches a warp and woof of easy pathways, the decision of which of them will be utilized, and in what force and microdistribution, is indeterminate, left to be decided at each branching point by the actual local competition for the limited supply of substance arriving from the common cell body. So, if the common source may have had a “program” for the attainment of the highly regular end result, the precise way of how to get there could certainly not have been spelled out in it in great detail. For those ways are different and unique for each of the millions of cells. The double meaning of the word “design” comes to our mind: design as purposeful planning at the start, ending in stereotyped design as accomplishment, but countless ways of execution leading from one to the other.

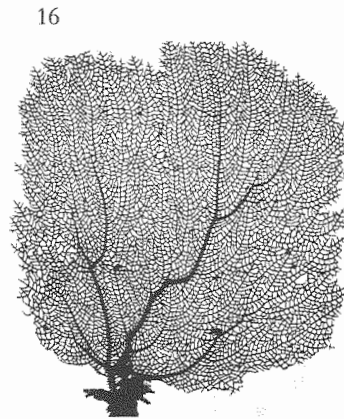
Extending our examples upward, Figure 16 pictures a lace coral—a limestone housing development of both



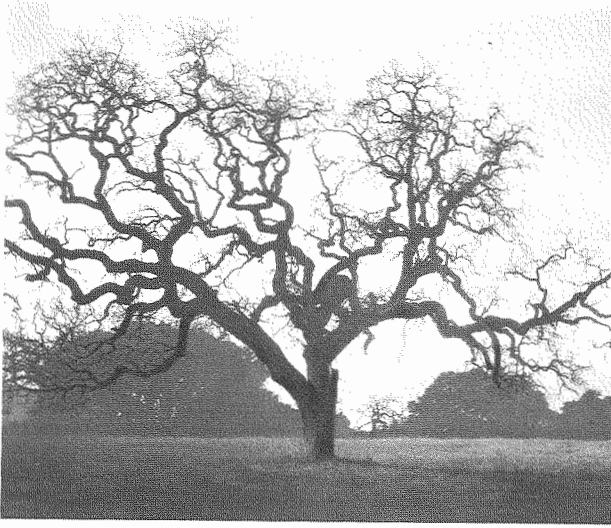
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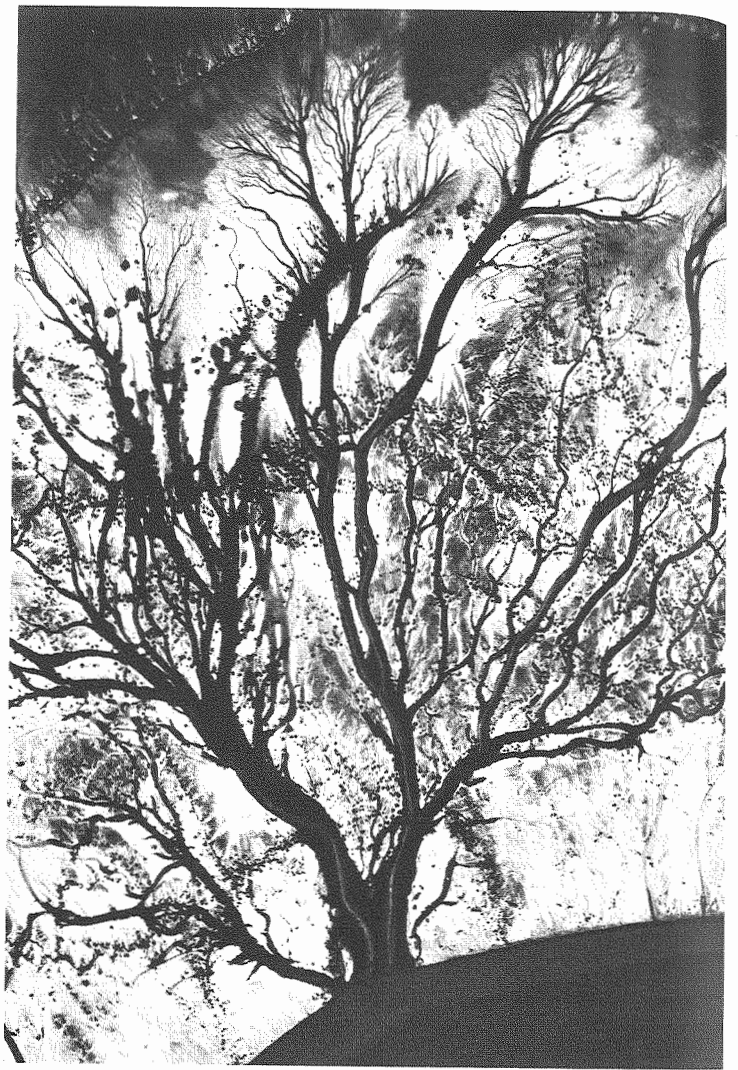
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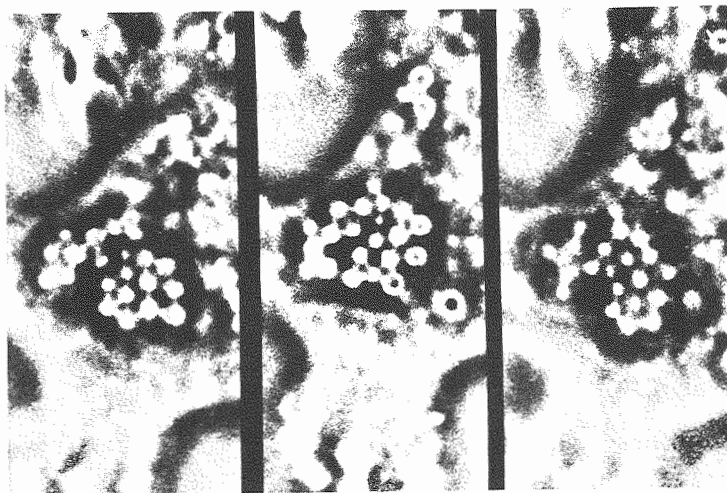
great over-all regularity and individual uniqueness, built by thousands of separate little animals in the colony in a concerted pattern of behavior. You may sense already my own design. It is to reorient thinking from static *form* to formative *behavior* across all orders of magnitude. The range extends beyond the coral colony to human society and to what I take to be its design for living, and indeed, survival: namely, to recognize that individual freedom in the *small* is compatible with the existence of collective order in the *gross*, which reconciles self-determination of the individual with the much stricter frame of rules descriptive of his group.

Were it not for this principle of nature, were the development of every part or branch allowed to pursue its own capricious course without constraints, without a frame of integral interdependencies, we could not have

trees (Figure 17) that we could categorize distinctly by their shapes as oaks or pines or poplars even though each specimen is individually unique. Such stereotyped end form defies any logical attempt to regard the product as just the blind outcome of a bunch, or call it a sum, of microprecisely programed cause-effect sequences of linear chain reactions in the sense of a naive mechanical machine concept.

The conclusion that countless constellations of convergent microevents may yield macroproducts of essentially the same standard pattern makes it, by the same token, gratuitous to assume that similar terminal patterns must have had similar mechanisms and histories in common. The treelike pattern of the Colorado River delta (Figure 18) will prove the point. Let us go on then and reverse the outgrowth pattern of the tree and we obtain the picture of a river forming by junctions of tributaries from many sources; but also, similarly, the inverse "arborization" of cracks in crystals advancing from edge to interior in stepwise confluence (Figure 19) from top to bottom.

Let us now move up to the next step of complexity. Our past examples have been relatively simple. They dealt with interactions among parts of systems which, after all, were still connected and continuous in substance—blood vessels, leaf veins, trees, rivers, etc. Order emerging in complexes of disconnected, discrete units taxes our explanatory faculties far more severely. As introduction to the subject, I chose Figure 20—three frames from a motion picture film of one and the same cell in tissue culture at brief intervals. They show a group of granules, each about one micron in size. These granules are separate bodies, freely mobile, bouncing around in the soft cell plasma. But as they change positions, they assume preferentially characteristic geometric group configurations—mostly hexagonal, but intermittently an occasional square. Now, since they are separated by appreciable distances, we must infer that in their random buffeting by Brownian motion, they are transitionally stabilized—trapped, as it were—at equidistant equilibrium points in a field of



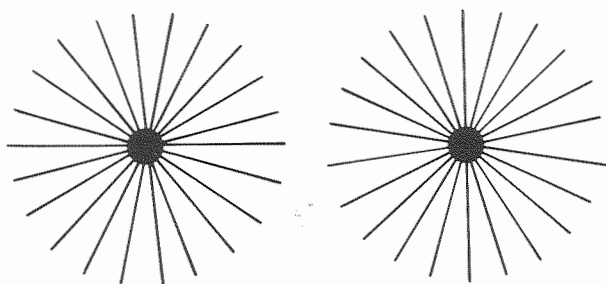
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forces established by their mutual interactions, like partners in a square dance or quadrille. If this sounds vague, consider that we can at least describe the various fleeting configurations with relative precision, even though we do not know the actual dynamics defining the grid.

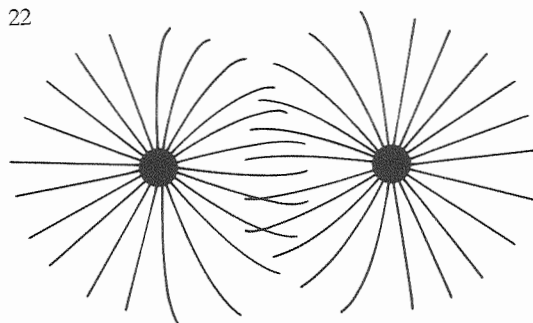
There are other cases, however, in which the operation of group dynamics has lent itself to more concrete definition. Since they demonstrate most cogently that going beyond the one-plus-one-equals-two rule does not mean giving up scientific discipline for the outer space of supernaturalism, I shall dwell on them somewhat more extensively.

Let us take two bodies (Figure 21), as centers of emanations and force fields extending radially into the environment, and let them move toward each other from a great distance. Beyond a certain range, interactions between the two are as negligible as the effect of gravitational attraction by the moon is on our stance. Yet as we bring them closer (Figure 22) and as the overlap of their domains increases, their joint effects depart increasingly from the result one would expect from a sheer superposition and algebraic summation of their single contributions. They mutually distort each other's sovereign patterns of action.

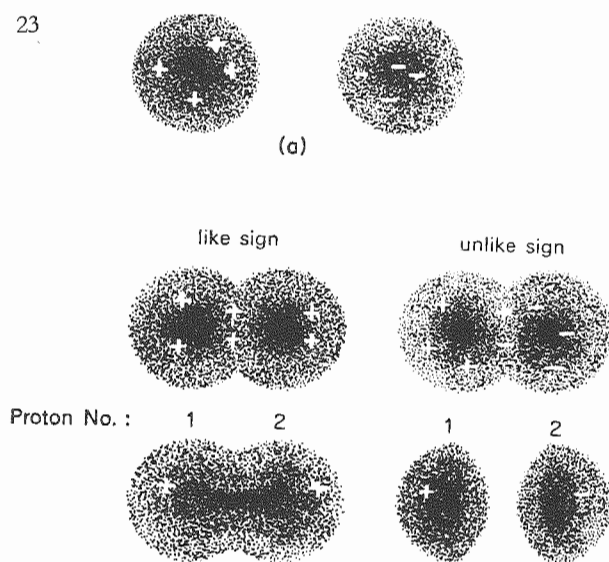
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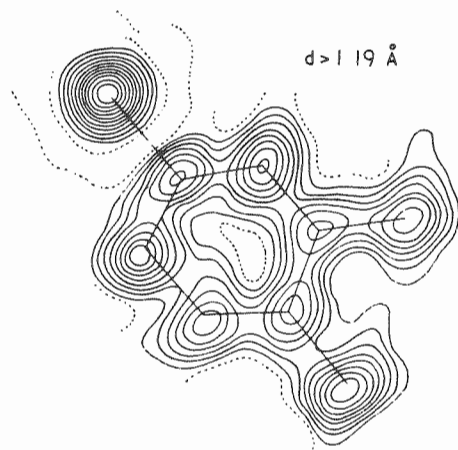
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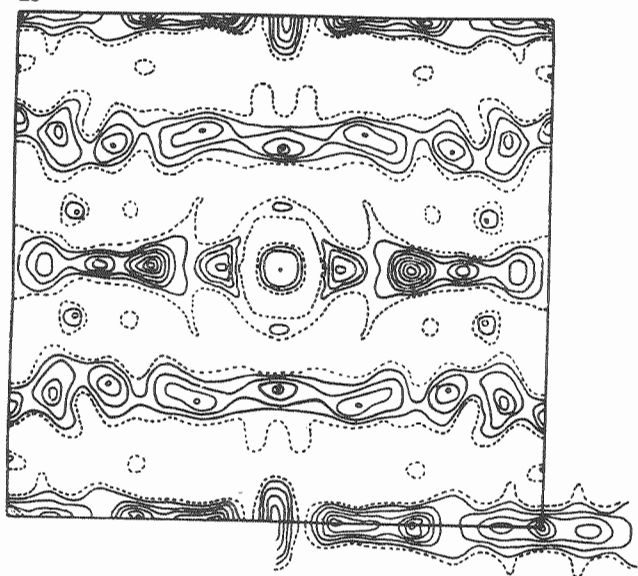
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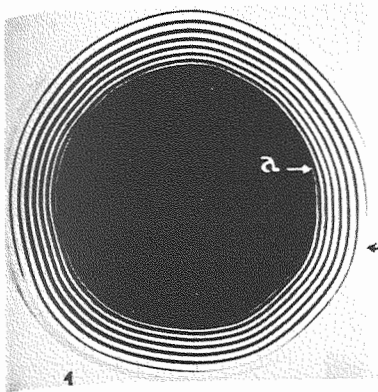


In atomic dimensions, for instance, this yields the redistribution of electrons between atoms (ligand fields), deforming the erstwhile spherical electron clouds, as shown in Figure 23 (bottom line). The dumbbell-shaped interaction pattern seen in the figure at the left is typical of many cases. The next picture (Figure 24) shows the mapping of electron distribution in a small organic molecule (specifically a diaminochloropyrimidine). Such a continuous field pattern emerges from the group interaction of the constituent atoms and atomic groups, which formerly were envisaged and represented as discrete, neatly bounded entities. More complex molecules—for instance, the protein, myoglobin, shown in Figure 25 in the so-called Patterson projection of its subunit fields—yield maps of still more sophisticated collective fingerprints. One is reminded of the contour maps of mountain ranges. Domains of particles are no more truly isolated than are mountain peaks.

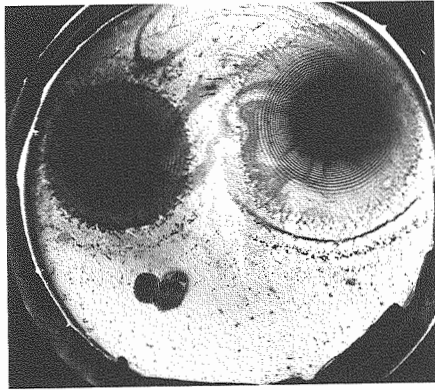
My reason for showing these diagrams is that they express symbolically that patterned processes in space and time form *continua*. To single out and fence in mentally, in such continua, peaks, centers, foci, or what not, corporeally isolated from their context, has long been a legitimate abstraction of immense tactical and practical utility in science. Yet, he who forgets that it is basically an abstraction could as well end up trying to extract the center of gravity from a body. One recognizes a kinship between this trend and some of the old notions, still not totally extinct, about brain centers as the “seats” of specific functions.

Familiar and accepted as the preceding propositions are for the molecular realm, their equal validity for higher levels, through the cellular to the social, has rarely been pointed up, let alone studied and conclusively proven.

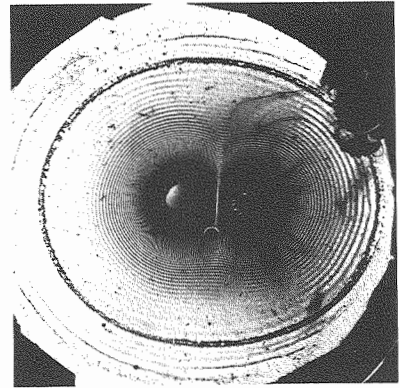
Let me again start from an inorganic model, the so-called rings of Liesegang (Figure 26). A drop of silver salt dropped on a gelatin plate that had been soaked in a chromate solution lays down, as it slowly diffuses, periodic concentric rings of insoluble silver chromate. The rhythmic character stems from some sort of threshold phenomenon, formally comparable to the rhythmic response of nerve tissue to a constant stimulus. If we place *two* such diffusion centers sufficiently far apart on a common plate (Figure 27), the total pattern still adds up, in the main, to one-plus-one. Yet, if we narrow the original distance between them, their mutual interference becomes conspicuous (Figure 28): the twin set of circles becomes distorted, the more peripheral ones merge to single dumbbell-shaped contour lines, and the outermost and farthest advanced form a smooth enclosure of both. The two domains have fused. Carrying on the tests, I then placed seven drops on a plate in the configuration of the Great Dipper. Figure 29 shows the outcome of an actual experiment.



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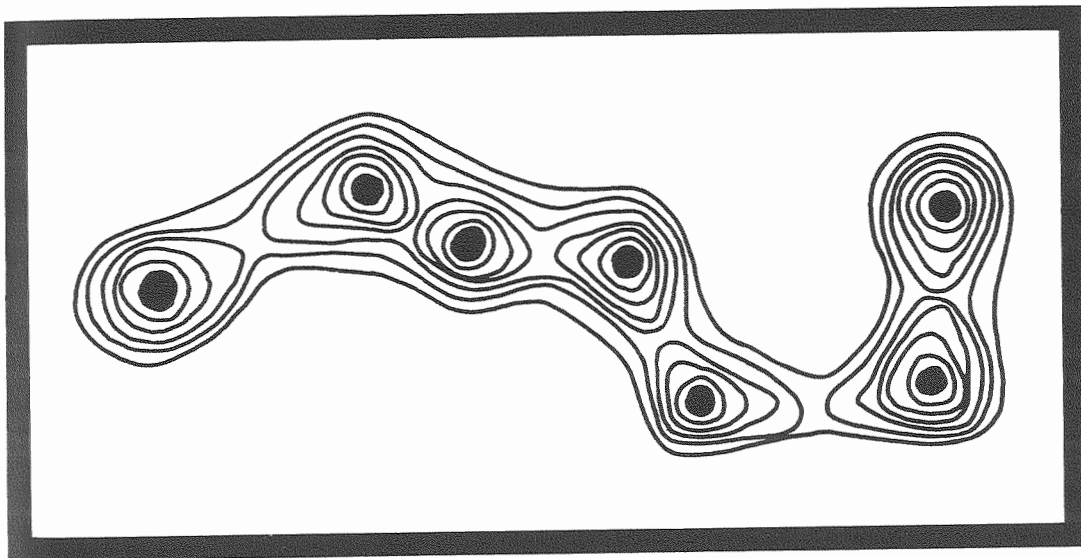
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As one notes, the resulting pattern of silver lines coincides with the pattern of point connections that led man to give the stellar group its name. Does not the unequivocal of this correspondence intimate that a similar dynamic interaction pattern in man's brain had guided his interpretation? Stars do register on retina and brain as single points, but may not the several neural processes thereby actuated engender, on a higher brain level, dynamic interactions that integrate an erstwhile mosaic of local dots into a unitary spatial pattern?

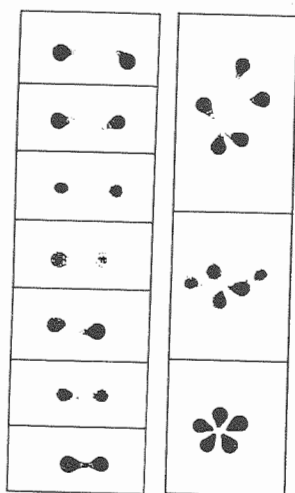
At times, proposals for such physiological underpinnings of Gestalt phenomena have been set forth, couched

mostly in symbolic terms of field concepts and related models. Experimental verification, however, has remained scanty. Because cell types other than neurons have furnished far more factual examples of how pattern-determining field effects can arise, I shall turn to those. I shall present two major types of patterning interactions among dispersed cells, first, in a liquid (thermally agitated) environment and second, in a firm cohesive matrix.

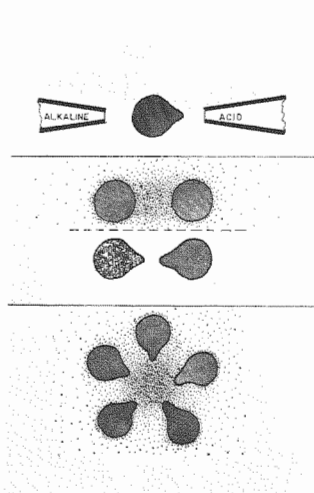
The earliest morphogenetic step in the egg of the seaweed *Fucus* is the sprouting of a rootlet on one side. In isolated eggs this sprouting takes place at quite a random spot. When several eggs are combined in groups, how-



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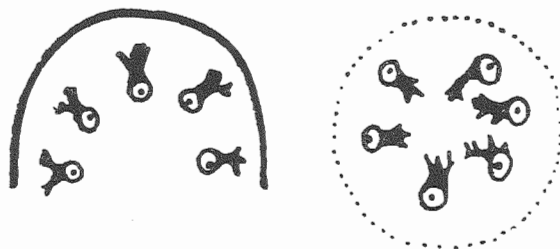
ever, sprouting is patterned. As Whitaker has shown, pairs of eggs in close proximity sprout at the sides facing each other (Figure 30). However, huddles of more than two sprout toward the geometric center of the group (Figure 30). Thus "mutual attraction," which might still have been conceivable within pairs, is clearly ruled out as explanation for groups of more than two. How then can one account for the phenomenon? Quite simply. When Whitaker placed undivided eggs into a pH gradient (Figure 31), the rootlets sprouted at the more acid side, perhaps because the egg membrane was weakened on that side and sprang a leak through which the rootlet could hatch. Now, eggs may be assumed to secrete their own acid as a metabolic product. This acid cannot diffuse from the confined space within a cluster as rapidly as it can from the outer shore. As a result, an inner-to-outer concentration gradient of acid will develop and polarize the members of the group toward their common center. The additional step that the experimenter had to take to localize root formation the eggs perform among themselves in concert, thus adding what makes two different from one-plus-one, and even three different from the new two-plus-one.

In clusters of explanted embryonic nerve cells (Figure 32), Stefanelli observed a similar convergent growth of dendrites toward the common center, but only if they were not near the outer edge of the drop of culture medium; for near that border, competition between the inner medium and its outer environment apparently reversed the gradient, and the dendrites consequently grew outward. The actual agents involved here have not been determined. For other tissue cells, however, we could prove (Figure 33) that bipolar cells in culture, acidified at

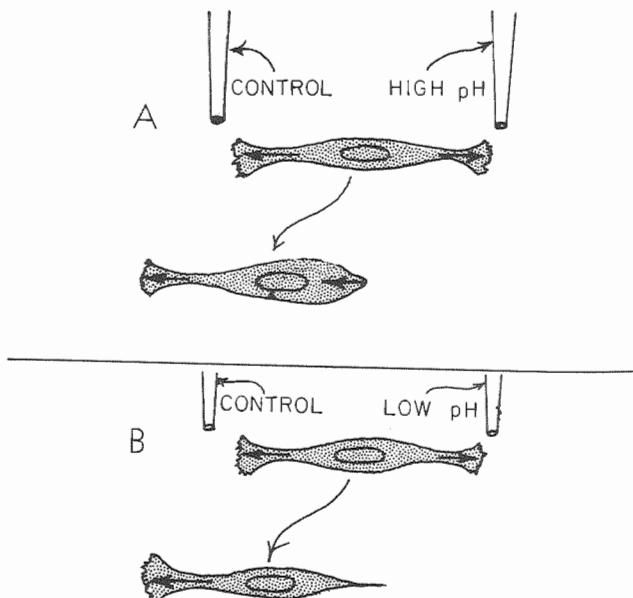
one end, withdraw that process, thus becoming unipolar. This fairly reproduces what two cells exuding acid will do to each other as soon as they come close enough. Of course, exudates other than acids could have the same polarizing group effect.

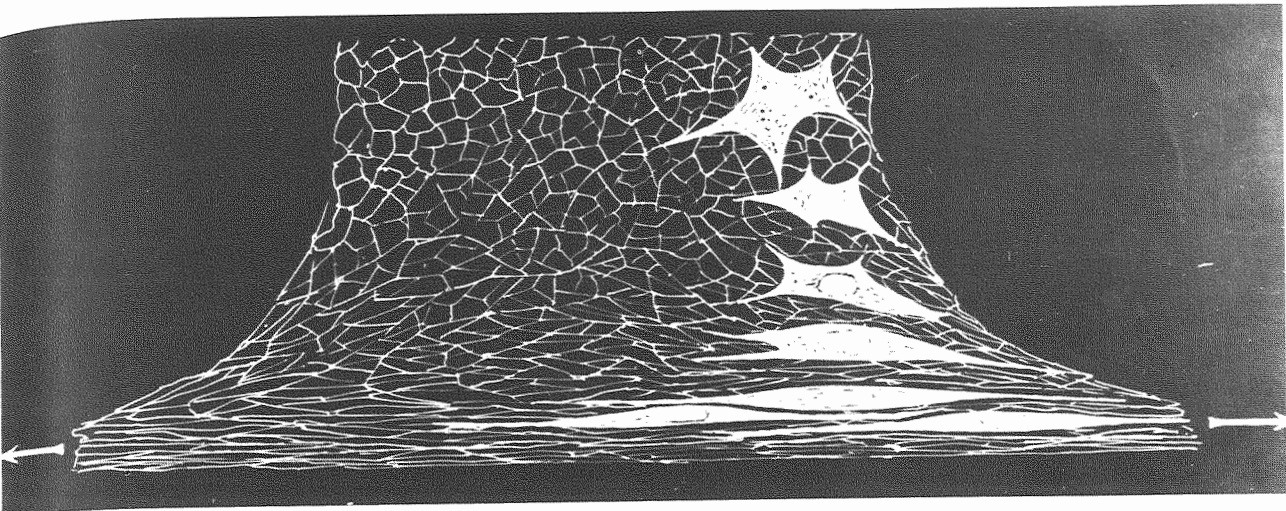
Group patterns among cells in semisolid media arise differently. Most tissue cells, as well as nerve fibers, need the support of solid structures—fibrin or collagen fibers, for instance, along which they move and grow, like plants along a trellis. The diagram in Figure 34 summarizes the gist of four decades of experiments on this principle of "contact guidance." An untreated protein coagulum, e.g., fibrin in a blood clot, is a random tangle of fibers (top of figure). As illustrated in the lower part, stretch orients the mesh in the direction of the lines of stress. Depending for guidance, like blind men, on the fibrous tracks, the cells then trace the underlying structure. Cell group patterns thus have their precursors in the fibrous matrix in which they are enmeshed. Therefore, if cells could do to the ma-

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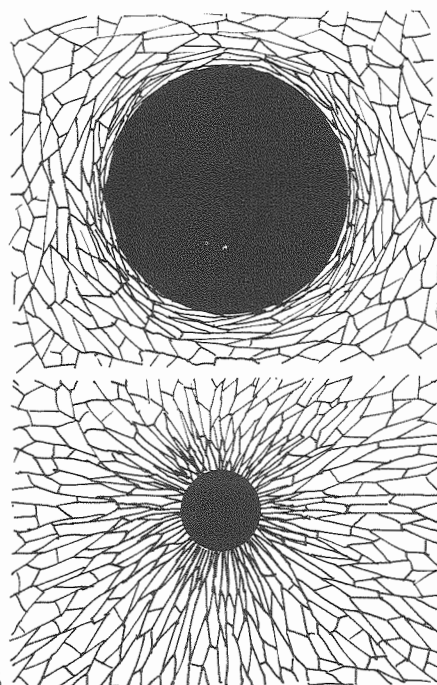
trix what the experimenter does in applying stretch, they could evidently manage to set up their own physical interconnections and group patterns. And indeed, they can do this. Here is how.

A cohesive fibrous network is under internal tension. Any local disruption of the net makes the surrounding meshes retract to form a ring around the hole, as any lady knows from holes in her stockings. Some spiders (Figure 35) use this as a trick to build a strong-walled nest. Now, cells can achieve the same result, where needed, by local liquefaction through proteolysis of their matrix, or just by local expansion (Figure 36). Many fibrous and muscular coats around hollow organs owe their circumferential orientation to this effect. More pertinent for us here is the bottom diagram, which illustrates local shrinkage. The meshes are gathered purse string fashion, assuming a radial orientation with focus on the shrinking center. Now, some cells, especially proliferating ones, make their surrounding matrix shrink in just this fashion by the release of chemicals that make the meshes squeeze out water, like setting jelly. If cells subsequently emigrate from such a center, they naturally follow their self-created radial routes.

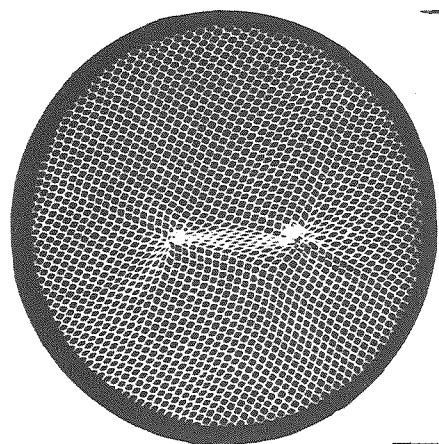
Now, if there are two such cell clusters in a common matrix, will the resulting growth pattern turn out two overlapping stars? Of course not. Let me recall the diagram with which I introduced the two-center theorem earlier in the article (Figures 21 and 22). Two local centers



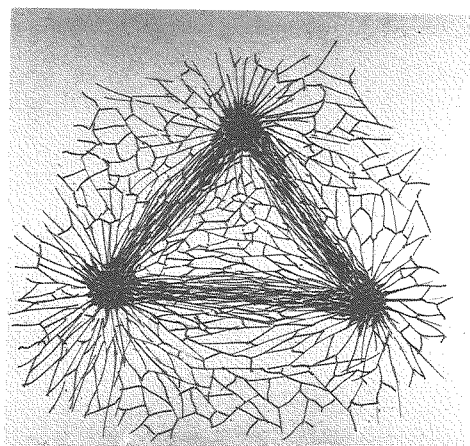
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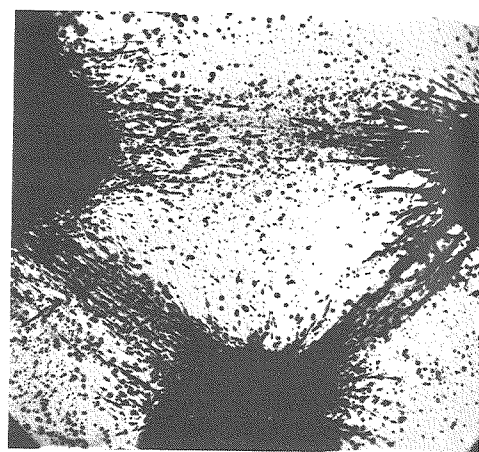
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of contraction in the net decidedly do not add up in their effects, as can be demonstrated readily by gathering a taut piece of mesh fabric at two points (Figure 37): the meshes between the two centers are distorted lengthwise into a straight course along the connecting line. In the same way, two clumps of growing cells force fibers in their common colloidal medium to assume a straightline orientation along the shortest distance between them. Three centers generate a structural triangle in their matrix (Figure 38), which then serves as roadway for emigrating cells. Thus, three scalar and erstwhile unrelated local chemical activities become upgraded through vectorial interaction into a well-defined space pattern emerging *de novo*. Figure 39 shows an actual case of such an automatically established triangular interconnection among three embryonic spinal ganglia in vitro.

The "beeline" taken by outgrowing cells toward the distant colonies is simply a result of contact guidance. It is definitely not to be credited to any hypothetical "alluring" substances that might have emanated from the distant sources acting as beacons; but there is recent evidence that straight fiber bundles can expedite chemical traffic along their surfaces. So, secondarily, the cell population along the fibrous bridges does gain ulterior benefits from its earlier highway construction. Quite generally in development, structural order, once it has been established, creates conditions for its self-promotion and further elaboration.

The architectural effects of a two-center interaction are noticeable in populations at all levels from the molecular to the human. The earliest chromatograms, made by the chemist Runge more than a century ago by letting mixtures of substances diffuse on filter paper, are an example (Figure 40). The confluence of the edges of diffusion from two separate centers immediately sets up a communicating channel, which then drains further substance seepage into

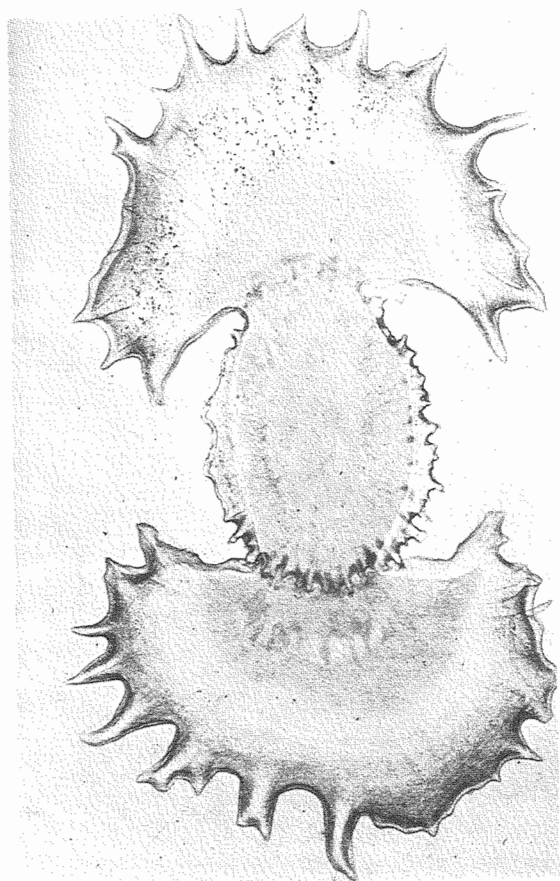
its bed. The resulting pattern, reproduced here from one of Runge's original experiments, closely resembles the pattern of mitotic spindles in cell division. Coincidence? Perhaps, but worthy of attention anyhow. And curiously, a recent architectural proposal by Catalano (Figure 41) for the most efficient structure of a modern growing bicentric city embodies a remarkably similar symmetric pattern of settlement along pressure and flow lines of communication. Population and market distribution between two actual towns, mapped to scale by Isard (Figure 42) bears further witness to the operation of the two-center effect in the dynamics of human ecology.

This mention of ecology brings me to my last set of examples. Ecology is group behavior in free interaction with other groups and with environment. It epitomizes the lifting of subject matter from sheer catalogues of items to paramount concern with their typical differential distribution and, digging deeper, with the patterns of the underlying dynamics. Behavior patterns are ecology's instruments. To explain life, static cell anatomy must become molecular ecology, organisms be comprehended through cell ecology, and societies through the dynamics of human ecology. They all provide us with examples of rigorous scientific propositions that hold for groups but dissolve when efforts are made to reduce them to elemental properties. Here resolution becomes sheer dissolution.

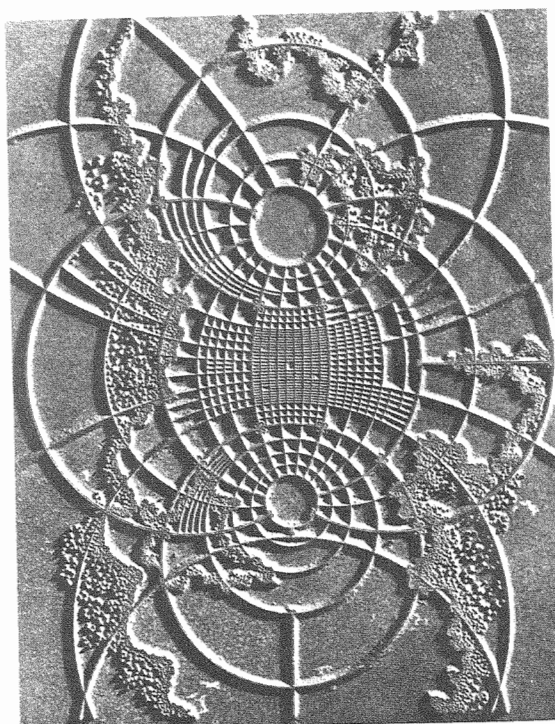
Let us then be emphatic: True, scientific history has grooved our habit of explaining group behavior in terms of the interactive behavior of quasi-independent unit actors, whether molecules or men. Yet this pragmatic, conceptual artifact has serious limitations, and once we reach the limits of its applicability we must relax our historical commitment to exclusive legal recognition of conclusions arrived at analytically and must concede equal explanatory

status to collective statements of fact in their own right. Modern physics has done it implicitly in adopting thermodynamics, quantum theory, relativity, and statistical mechanics, and the time has come when the life sciences had better follow suit for their own good. They must learn to accept recognized orderliness of the behavior of systems on its own terms. If they can reduce it to analytical terms, well and good. If not, the reality of nature still must be allowed to prevail and override pet micromechanistic preconceptions based on predilections. Therefore, regardless

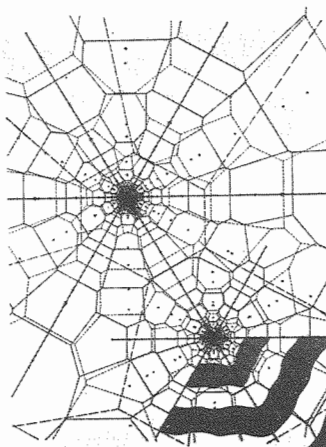
of whether ordered behavior patterns of systems will yield to obstinate analytical efforts at piecing them together through sheer assembly of component pieces—whether of molecules joining to form specific macromolecular systems, of cells to compose organs, or of neuronal circuits to yield adaptive functions—the integral formulations will retain their claim to reality and primacy. Both conceptually and historically, reductionist description is a secondary and limited tactical convenience. Its limits are to be determined empirically and not by prejudice.



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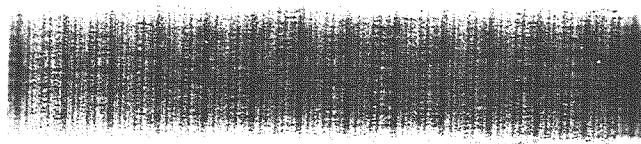
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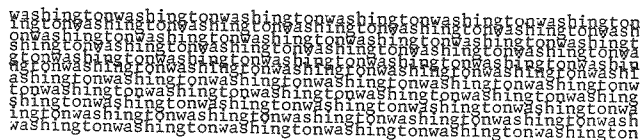
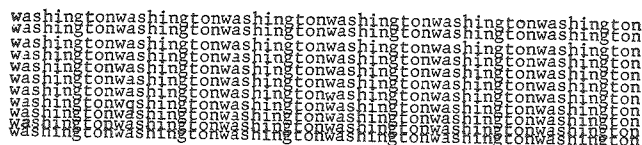
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Let me briefly pursue this matter on the example of linear arrays, already mentioned briefly earlier. Collagen fibers (Figure 43) are bundles of polymeric chains of protein molecules, linked head to tail and flank to flank. Under certain conditions, homologous subgroups of neighboring chains line up in register, resulting in conspicuous cross-banding. Each molecule is characterized by a specific sequence of amino acids along its backbone. The sequential order being commonly referred to as a code, it justly can be compared to the sequence of letters in a word. Register, then, signifies the sliding of identical letters into

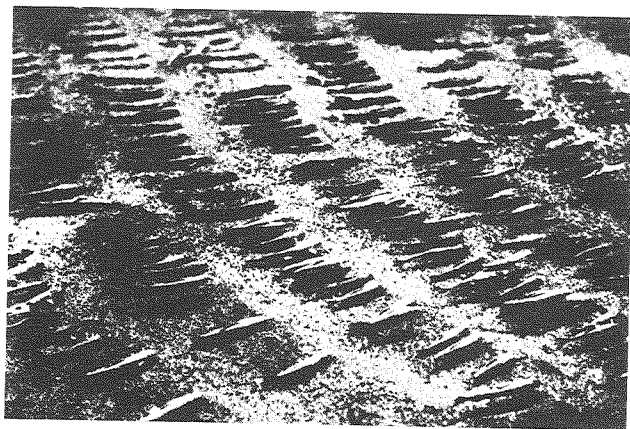
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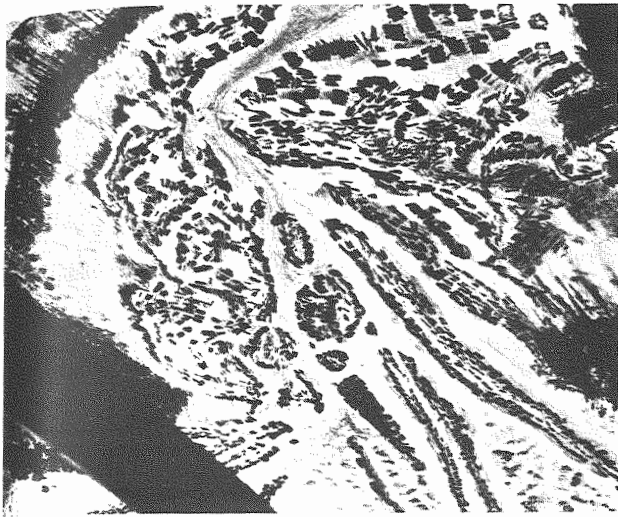
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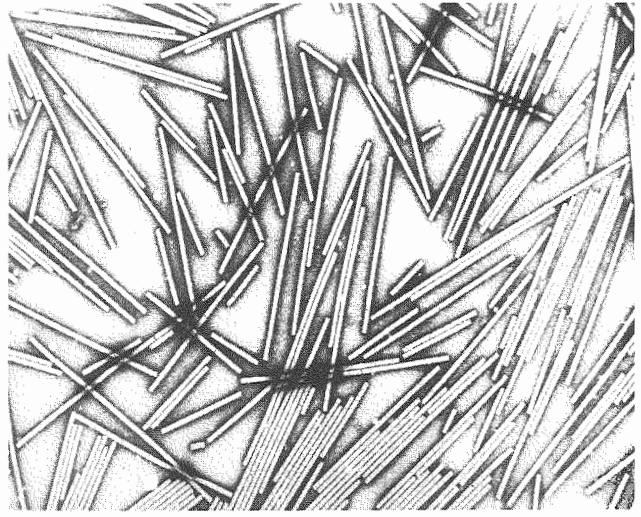
alignment (Figure 44), and there is good reason to expect that the molecular mechanism of zipping collagen fibril to fibril by site-matching will be revealed before long. This instance of higher group order then resolves itself simply into a case of assemblage by the orderly stacking of contiguous elements, not unlike our initial examples. But what if similar ordered arrays arise in collectives of linear units without the benefit of mutual contact? How to explain, for instance, the corresponding group pattern of freely mobile, well-separated, linear units in Figure 45, which shows an assembly of trout evenly spaced in parallel and register on the bottom of a stream? Clearly, current flow lines and interindividual signals combine in yielding this behavior pattern in grid form, but just how is wholly obscure. How far, then, can we carry the notion of synthesis of such group patterns through the free interaction of their unit elements?

Figure 46 presents an aerial photograph of logging in the Columbia River. The logs are all aligned by current flow and shore lines. Their deposit in register is man-made. In other words, the collective order is strictly imposed by outside forces, which makes it irrelevant to our present context. Not so the next example. Figure 47 is an electron micrograph of rod-shaped tobacco mosaic virus. The units are clustered, and within each cluster the component rodlets are again both in alignment and in register. They look like match sticks; and indeed a group of matches can by analogy serve as a model of the physical mechanism through which such a simple step of order in self-assembling groups can come about. If one scatters matches at random on the surface of water in a dish and then agitates the surface by continuous tapping on the container, the floating matches get into motion and as they collide, they turn into positions of mutual alignment and register—positions evidently satisfying an equilibrium (minimum surface energy) requirement for that particular three-phase (water-wood-air) system. Three stills from a motion picture film of such a model experiment are reproduced in Figure 48, to show the progress in the increase of order by “self-ordering.”

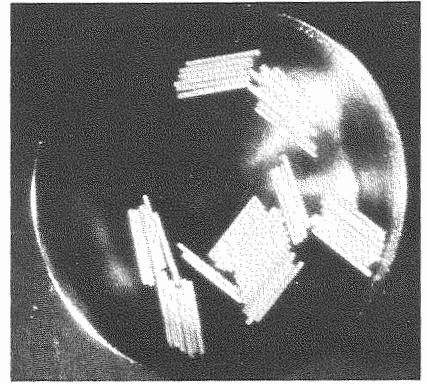
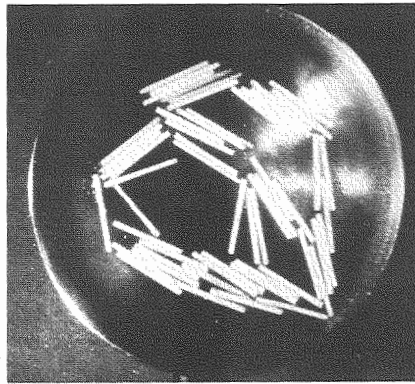
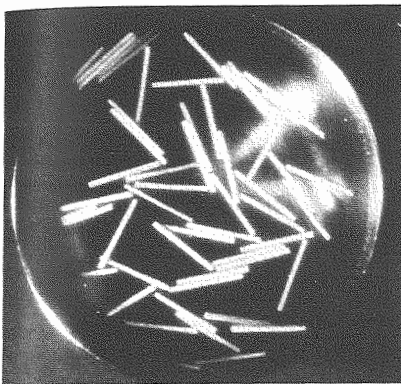
Being an instance of ordered group behavior emerging visibly from elementary interactions, the case surely is heartening to reductionist faith. Unfortunately, the argument is open-ended, as can be readily observed in motion pictures of a remarkable rod-shaped microbe, *Bacillus circulans*. Loosely scattered bacilli start out by assembling in physical arrays just like those matches (Figure 49), but once the group has enlarged to a certain critical size, the whole mass adopts a totally different course of behavior: it begins to circle around its own geometric center as fulcrum and keeps on rotating for indefinite periods of time (Figure 50), like a revolving disk, regardless of whether



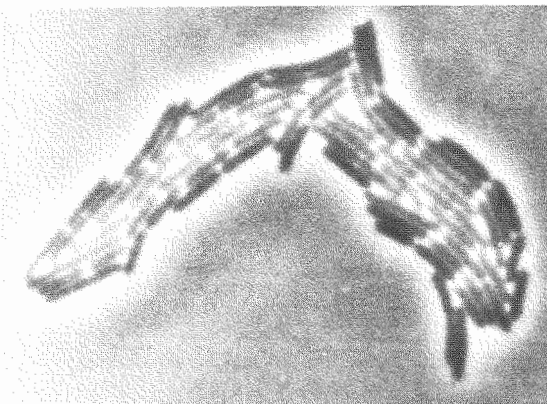
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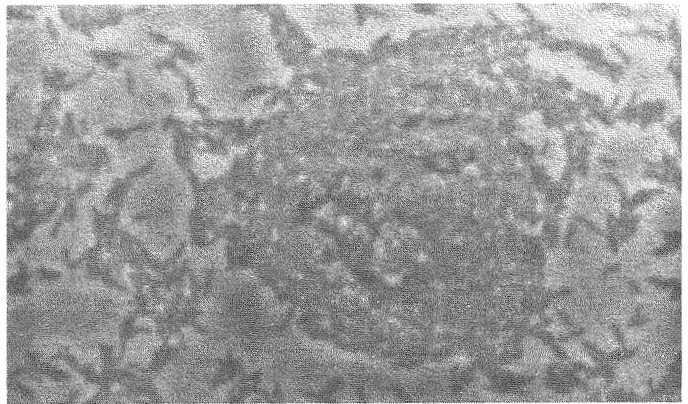
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the number of individuals are counted by the hundreds or hundred thousands. There is no sign in the behavior of individuals before their assembly that would have intimated the future rotatory performance of the collective. In fact, although each spinning mass tends to keep its sense

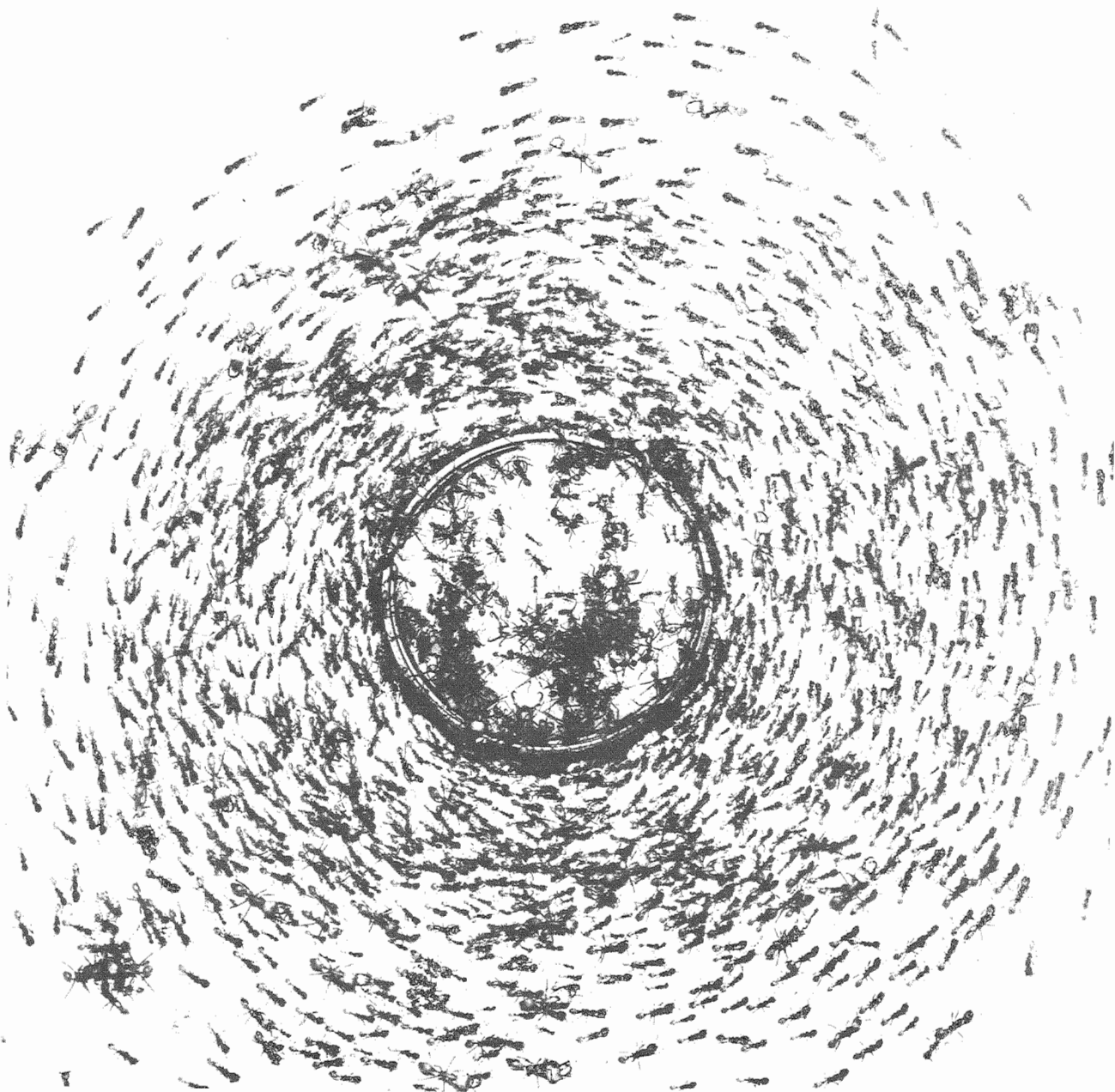
of rotation once it has been started, whether clockwise or counterclockwise, fragments that split off may change to spinning in the reverse direction. So evidently the individual units are totally uninstructed as to the direction in which they will be made to spin by their assembled com-

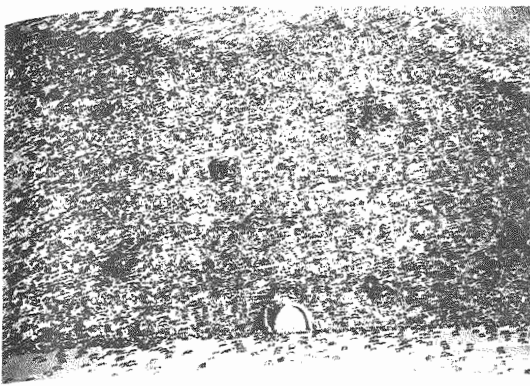
munity. Here we are faced with true emergent novelty

The circling motion of masses of army ants is equally instructive (Figure 51). They keep running round and round a central column, drawing in stragglers, leaving others behind, in an interminable mass circus movement. The infectious pattern of these insect dervish exercises is spectacular. Unfortunately, this running in circles finds a

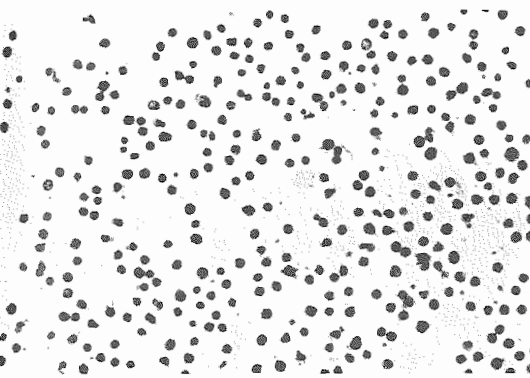
counterpart in human affairs. In fact, in general, there is not too much difference between the laws of human ecology and the ecology of cells and molecules. Dependence on environment, self-sorting by segregation, compounding in groups, recombining for symbiotic reciprocity—in short, self-patterning of groups—occurs among molecules and men alike.

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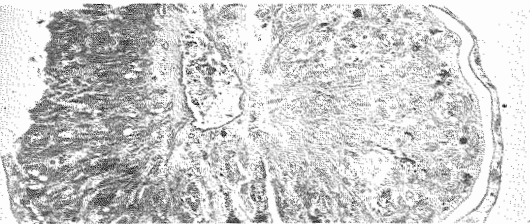




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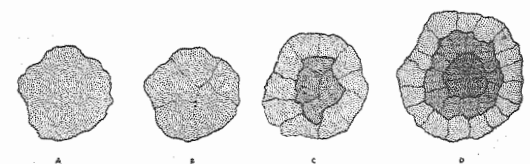
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Take, for instance, this aerial view of Coney Island on a Sunday (Figure 52). Consider the people as molecules. The heavier border on top is the condensed belt of hydrophobic bodies adsorbed to the water-beach interface. The dark clusters inside the mass clearly mark domains of attractive forces, presumably emanating from sources of nutrient and stimulant attractants. Their equidistant spacing indicates mutual repulsion through forces of competition; and so forth. The analogy is not at all facetious. It cuts deep into the heart of our topic, for it exemplifies basic features of self-organizing systems. I could have gone on, for instance, to relate how a random mixture of isolated single cells (Figure 53), obtained by dissociating an already functioning embryonic kidney, then scrambled, lumped and properly nourished, can reconstitute itself into a remarkably well-organized miniature kidney (Figure 54); or how similarly scrambled cells of embryonic chick skin in tissue culture can grow into normal feathers (Figure 55); all of this entirely by "do-it-yourself" methods.

Examples of "self-organization" of this kind are numerous. To label them is easy, although gratuitous. To understand them is a long way off. Exclusively reductionist tactics will never get us there, if they persist in "going it alone"; nor, on the other hand, will sheer verbal soporifics. What the task calls for is, first of all, a job of thorough conceptual overhauling and renovation. It requires that we drop self-imposed blinders and admit to view the higher perspective of the whole—not just its bogus literary versions, but its hard scientific core, expressed in such phenomena of emergent collective order as I have illustrated. The venal preoccupation with bits of the materials of nature as such—with "what there is"—must give way to a broader concern with the manner of their operation and use—with "how it all works." And, in this shift of emphasis, one discovers that all the bits hang together; that they are all intermeshed in webs of subtle interactions forming domains or subsystems within the over-all continuum of the universe.

To emphasize the "systems" character of the dynamics of living entities I have, ever since 1923, couched their description in terms of the concept of "fields." Lest this symbolic term again arouse alarm, let me decontaminate it instantly by the following simple example (Figure 56). Let us take a circumscribed body, depending for its maintenance on active exchange with its environment; for instance, an egg in the ocean, a cell in a tissue, a human individual in society. Then let the unit multiply into a few more units; they all continue to have a share in the common interface of exchange and communication with the medium. But let the number of units keep on increasing, whether by subdivision or accretion, and all of a sudden a critical stage arises at which some of the units find themselves abruptly

crowded inward, cut off completely from direct contact with their former vital environment by an outer layer of their fellows. The latter thereby acquire positions not only geometrically intermediary, but functionally mediatory, between the ambient medium and the now inner units. From then on, "inner" and "outer" units are no longer alike. A monotonic group of equals has become dichotomized into unequal sets. With the emergence of the distinction between innerness and outerness, the $1 + 1 = 2$ rule becomes inapplicable.

The train of events to follow such a "differentiation" of a radially symmetrical core-crust dichotomy is easy to envisage. Interactions between the "outer" members and their newly established "inner" neighbors would expose to another set of new conditions any fresh units arising subsequently in the intermediate zone between them, and hence call forth in them a third type of reaction. Moreover, polarized influences from the environment (e.g., gradients such as illustrated above for cell orientation) would impose an axiate pattern upon the group. Thus would ensue a train of sequelae of ever-mounting, self-ordering complexity. In all these steps, the fate of a given unit would be determined by its response to the specific conditions prevailing at the site in which it has come to lie, those conditions varying locally as functions of the total configuration of the system—its "field pattern," for short. This principle—long recognized empirically as a basic criterion of systems but not always fully appreciated in its implications—is commonly referred to as "position effect."

The main point to bear in mind is that none of the component members of the group, all erstwhile alike, can know their future courses and eventual fates in advance; can know whether they would become "inner" or "outer" or "intermediate." Nor does it matter for the resulting pattern of the complex as a whole, as is best illustrated by the process of twinning. By cutting in two the cluster of cells that constitutes an early embryo or an organ rudiment, one can obtain two fully formed embryos or two fully formed organs, the way the sorcerer's apprentice, in trying to kill the water-carrying broom by splitting it down the middle, got two busy whole brooms instead. What had been destined to form a single typical organism or organ has yielded two instead, each half assuming the organization of a well-proportioned whole. In principle, we can now understand why: because bisection through the middle has resulted in "innermost" cells coming to lie "outermost" again, whereupon the whole pattern of subsequent dynamic interactions has proceeded, reduced to half-scale in harmonious proportions. (Of course, the individual parts can respond to their new local cues appropriately only if their original positions in the un-

divided framework have not already single-tracked them into courses unresponsive to the new demands.)

An inorganic model of this process is, for instance, a sitting drop of mercury. Its convex, lens-shaped form results from equilibrium between opposing sets of forces—gravitation and adhesion, tending to spread the mass, and cohesion and surface tension, tending to hold it together. Disturb the equilibrium by cutting the liquid drop in two, and each half immediately restores its own equilibrium by assuming a convex lens-shape. But freeze the original lens-shaped drop solid before cutting, and then bisect, and each half will retain its former shape of half an oblate; the dynamics that do the remolding in the liquid drop are still at work, but deprived of their free mobility, the elements can no longer yield.

The example of twinning is just one illustration among many for the thesis that strict determinacy (or invariance) of a collective end state is fully reconcilable with indeterminacy (or variance) in detail of the component courses of events leading up to it—a thesis I have tried to contrast with the basic reductionist doctrine that a determinate end can only be reached as the blind outcome of a microprecisely determined tandem chain of component microevents. This latter doctrine, "microscopic" and micromechanistic in the old sense, just is not tenable in the light of facts unobscured by artificial blinders; and yet its popularity has grown steadily because of the indisputable proof that in the progress of science, as I said before, the artifact of reductionist abstraction has had a most signal pragmatic merit. But the time has come when we must check back with *real* nature to find what we have missed by adopting the short-sighted view of close-range analysis as the sole legitimate approach to insight into nature. My early introduction of the "field" concept into biology has aimed at no more than at offering a semantic therapeutic against the spread of this epidemic of myopia and constriction of the visual field, which leaves so many burning problems in the life sciences unattended. The "field" is a symbolic term for the unitary dynamics underlying ordered behavior of a collective, denoting properties lost in the process of its physical or purely intellectual dismemberment. Being descriptive of a property of natural systems, it must not be perverted into a supernatural principle; the study of those properties is, of course, an empirical task and not a literary pastime.

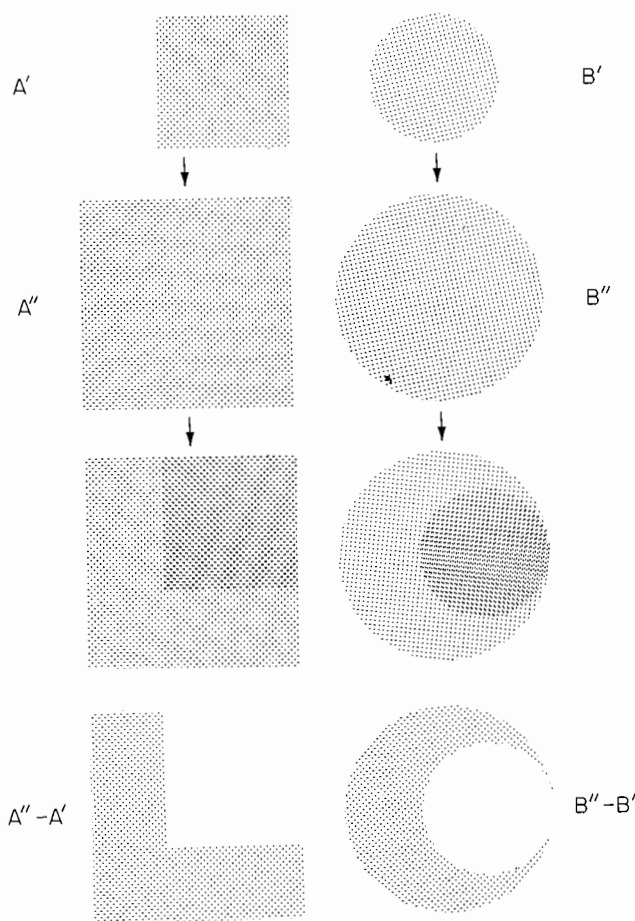
If the young generation were only to realize the origin of the microdissectionists' claim for a monopoly of insight into nature, more of them might turn to problems now kept out of their purview. So let me close with a brief anamnesis of the prevailing conceptual deficiency disease. To me, the crux seems to lie not so much in *a priori* reasoning as in our practice of phrasing experi-

mental results in some sort of shorthand language. I shall explain this on the schematic model of an experiment (Figure 57), right.

An experiment is motivated by our curiosity about the relationship between two phenomena of nature, A and B. We study them by changing A from A' to A'' and observe a correlated change of B' to B''. We then proceed to correlate the difference (A''—A') with the difference (B''—B'), these differences being represented by the cross-hatched areas in the diagram. And basically this is all we can extract from the experiment. But this is not the point at which we commonly stop. We usually go on to endow the *differentials* with an existence of their own, dissected from the context from which they were abstracted in the first place (bottom line in the diagram), and before we realize it, we have personified them as "actors." Genes for the difference between a white and a pink pea became simply genes for white and pink, respectively, throwing the peaness into discard; the differences between integrated brain functions before and after local lesions became transliterated to domiciles for specialist sub-functionaries, as if the rest of the brain were uninvolved; and so on.

In trying to restore the loss of information suffered by thus lifting isolated fragments out of context, we have assigned the job of reintegration to a corps of anthropomorphic gremlins. As a result, we are now plagued—or blessed, depending on one's party view—with countless demigods, like those in antiquity, doing the jobs we do not understand: the organizers, operators, inductors, repressors, promoters, regulators, etc.,—all prosthetic devices to make up for the amputations which we have allowed to be perpetrated on the organic wholeness, or to put it more innocuously, the "systems" character, of nature and of our thinking about nature.

May my presentation have succeeded in documenting that party lines drawn between emphasis either on the whole or on the parts are based on the artifice of predilection, rather than on the realities of nature. And may this realization find its way into human ecology, particularly its political branch, to prove that society is not called upon to choose between two extremes: either a license for



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anarchic random excursions of its component individuals, or the enforced subordination of individual members to a rigid group order dictated from above, but that, as in all organic systems, order in the gross emerges, not only in spite of, but as a result of, the interaction of free elements with freedom in the small, restrained only by common purpose—or call it program—and respect for nature, which after all, to speak in pre-Galilean terms, abhors not only a vacuum, but disharmony.