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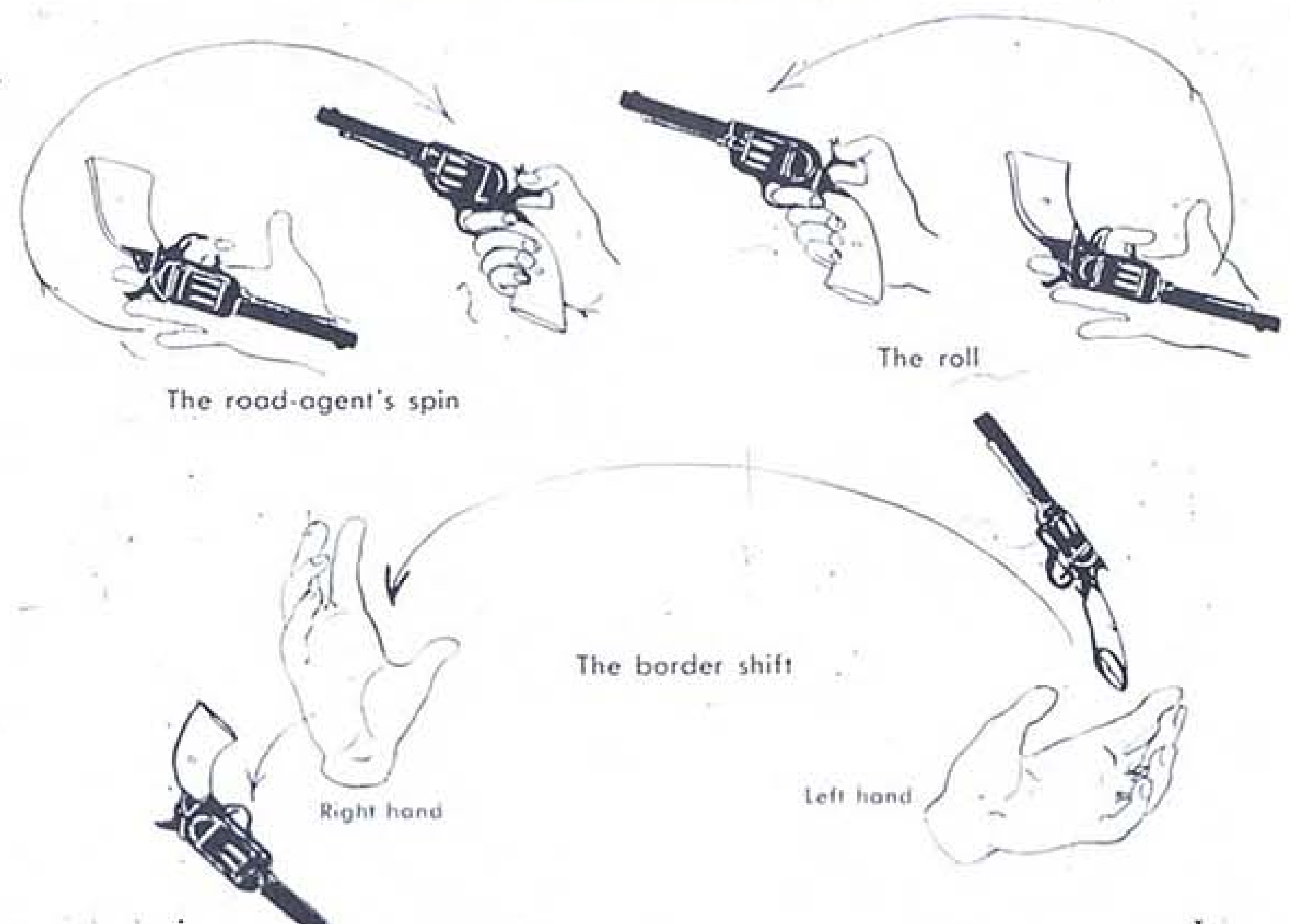
Geometry as a Nervous System

Lindy Roy



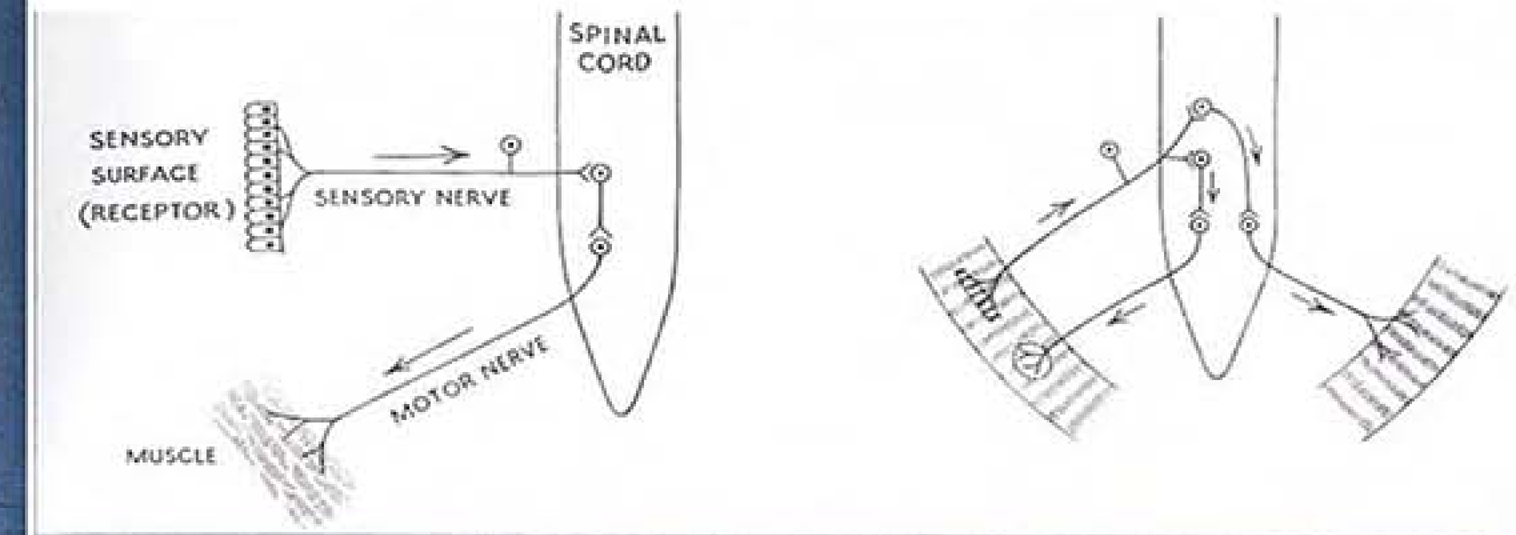
1. Reflex action

What is a stimulus? A stimulus is a physical record of an adaptation, specifically that of a sensitive system registering the difference between one momentary impression or attack upon it and another that just precedes it. Can the stimulus-world in which our behavior takes shape be seen to have a historical dimension? Perhaps so. The rapid crowding and kaleidoscoping of images and experiences that characterized the early-20th-century metropolis were both a physical and **psychoneurological condition. It was also, for example, the context in which Einstein's famous formulations, the special and general theories of relativity of 1905 and 1917, demolished even popular belief in the stability of the material universe. Einstein's argument held that objects change form when moving (with respect to a stationary reference frame), and furthermore, are even altered by the gravitational force of material bodies present within a given field. In the post-Einsteinian world there was no such thing as a stable body. Physical motion quite simply was seen as** transformative **– it both gave and deformed the space in which it occurred.**

A thing in motion therefore cannot be described by a conventional coordinate system. Coordinate systems, at least as we have come to know them, simply locate points in space, measure intervals of time and distance, and discern direction. In this classical expression, motion, always apprehended relative to a fixed coordinate axis, can only be frozen. Einstein preferred a plastic geometric reference system he called a "mollusc." He envisioned the unstable variable universe as a matrix of malleable, interpenetrating molluscs that continuously alter their shape in response to volatile, accelerating particles of constantly varying mass and proximity.

There may well be a set of xyz numbers, a three-figure address, for every point in three-dimensional space, but this does not mean space is those numbers. Space, even in scientific formulations, has long since ceased to be understood as invariant and passive. No longer simply the numerical substrate upon which actions are played out, space is unbounded. It is a restless matrix affecting, and affected by, the behaviors to which it gives form.

dome is very interesting, very good, worth copying many times over in the Soviet Union," Krushchev told news men as he pocketed one of the structure's brass rivets. "J. Buckingham Fuller [sic] should come here to lecture our engineers on his invention." – Robert Marks, "The Breakthrough"



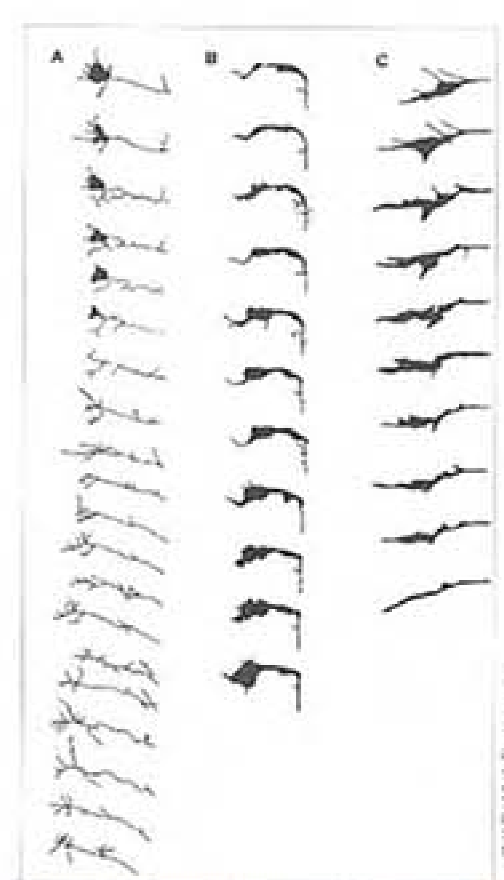
2. Sherrington's synergetic reflex
A single stimulus activates a simple reflex (left) while the same stimulus (right) activates a chain of individual reflexes.

Buckminster Fuller was among the first designers in the 20th century directly to confront the limitations of the Cartesian system. In the curious phenomenon of synergy – where the behavior of a whole is unpredicted by those of its parts, and where 1 + 1 might equal 4 or more – he saw the potential for a new generative geometry, able to deal with the integration and inter-activity of elements, that is, their productive, pattern-generating action in time. In *Synergetics: Explorations in the Geometry of Thinking* (1975) he claims: "Synergetics derives from experientially invoked mathematics . . . [and] shows how we may measure and coordinate omnirationally, energetically, arithmetically, geometrically, chemically, volumetrically, crystallographically, vectorally, topologically, and energy-quantum-wise. . . ."

THE REFLEX

And yet, it was in fact a neurophysiologist, Charles Scott Sherrington who coined the term *synergy*. The term, which literally means "joint action," was invented to explain the mysterious workings of one of the elementary units of an organism's coordinate behavior: the simple isolated reflex. His major work *The Integrative Action of the Nervous System* (1906) begins with a description of the simple reflex: a single stimulus that causes a reaction by means of one receptor and one effector while leaving the remainder of the organism completely unaffected. The simple reflex, however, was but a convenient abstraction for Sherrington. Fully aware that all parts of the nervous system are actually connected, and that no single part can react without effecting others, he noted that although reflexes are arguably the analytic units of all actions, they are no more than descriptive fictions. Sherrington had discovered that while a single reflex was an abstraction, the sum effect of many reflexes in a chain was real, each one *codetermined* by the others. Actual physical action, he argued, is effected by a *synergy* of reflexes – a holographic ensemble of interrelated and embedded scales of activity from which ordered movement arises.

Actions could no longer be seen as things made up of discrete and hierarchically arranged units but rather *relations* with densely nested and mysteriously interlocking properties. Reflex mechanisms, Sherrington surmised, are components in and of action, even if they never present themselves in a pure form. The concept of the "synergetic reflex" broke decisively with the mechanistic biological tradition (where physical motion was thought to be reducible to the sum of the participating anatomical parts) and set a new standard for the analysis of coordinated action in terms of imbricated neural processes. For Sherrington, the synergetic activity of the whole was not only quantitatively greater than the sum of its parts, it was actually *qualitatively* different as well. The *Reflex Arc* – comprised of a receptor, an effector, and the conducting nervous path that connects them – became the standard concept of the nervous system, its first elementary unit.



3. Synergy at work
The nerve cell, or neuron, is one of the most exotic and highly specialized of cells, distinguished in part by its electrical function. The neuron is also plastic. Cell parts are able to rapidly change form when linking up with other neurons in endlessly reconfigurable neural networks. The neuron has the capacity to run through an enormous repertoire of connective possibilities at extremely high speed. The morphology of the neuron branch tip of the *Xenopus* tadpole is captured here at three-second intervals. (reprinted with permission from John Wiley & Sons, Inc. Journal of Neuro biology, vol 31 1996)

RHYTHMS AND PULSES

Though neurobiologists at work during the first half of the century were reluctant to consider parts of the nervous system endogenously, that is, internally or spontaneously active, the fact that neural signals are spontaneously generated without outside stimulation is indisputable today. One example is the heart muscle, where so-called pacemaker cells in the muscle tissue emit rhythmic oscillations like an array of a thousand metronomes. Rhythmicity operates in living systems at myriad temporal and physical scales. From circadian rhythms that calibrate our metabolism to a 24-hour cycle, to cyclical patterns formed by stock market traders, it is ubiquitous in coordinated human activity of every kind. Rhythmicity has distinctive generative properties as well. During the second trimester of pregnancy, for instance, the fluctuating rhythmic pulsation of an expectant mother's orgasm performs a critical, generative function, patterning developmental data like an engram into the fetus.

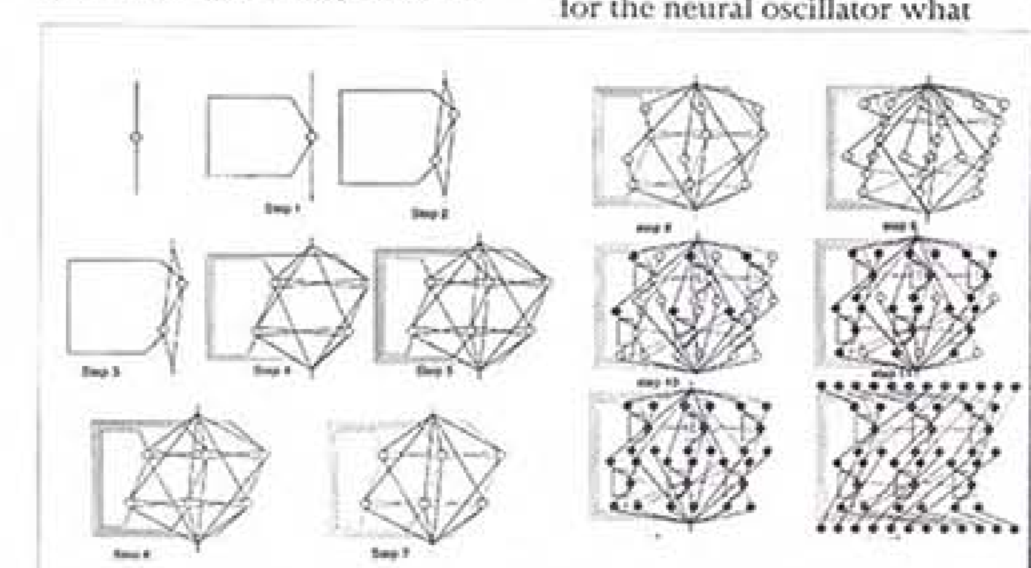
But mysterious phenomena such as these were largely ignored by researchers believing nervous media capable only of transmitting signals, never actually producing them. Large-scale coordinated activity was thought to be a matter of simple compounding or chaining together of individual isolated reflexes. This theory is of course totally incorrect; it ignores the many instances in the behavior of an organism where the response to a stimulus pursues a rhythmicity that has nothing to do with the cadence of the stimulus from which it ensues. The rhythm of scratching oneself, for example, is entirely independent of that of the stimulus producing the itch.

The early-20th-century theoretical biologist Jacob Johan von Uexküll, noticing the decidedly ambiguous relationship between a stimulus and the patterns of excitation that ensue, realized that a reaction was not simply triggered or fired by one fixed center of coordination. Instead, tiny internally generated rhythmic pulses implied that each small part of a nervous system was itself a mini reflex center. Coordination appeared to be located everywhere and nowhere at once. For von Uexküll, coordinated behavior was a consequence of certain regular, distributed criteria. It was variable, plastic, and flowing – something realizing itself over time and under certain conditions.[1]

Precisely how these fluid processes were regulated remained a mystery. Von Uexküll proposed the topographic concept of the *Tonustal*, or the "tonus valley," a model of displaceable fluids using gradients as a form of dynamic regulation. If nervous excitation is prevented from spreading in one part of an organism, it moves to another location as if in a valleyed landscape through which it naturally flows. Fuller's *Tensegrity*, or tensional integrities, can also be understood as systems of energy transfer in which energy fluxes regulate islands of compression in seas of tension. In the case of the *Tonustal*, the plastic distribution system comprises a variable nerve net across which impulses move, are caught, and take form rather than being transmitted in a linear chain reaction along a prescribed path as Sherrington earlier had thought.

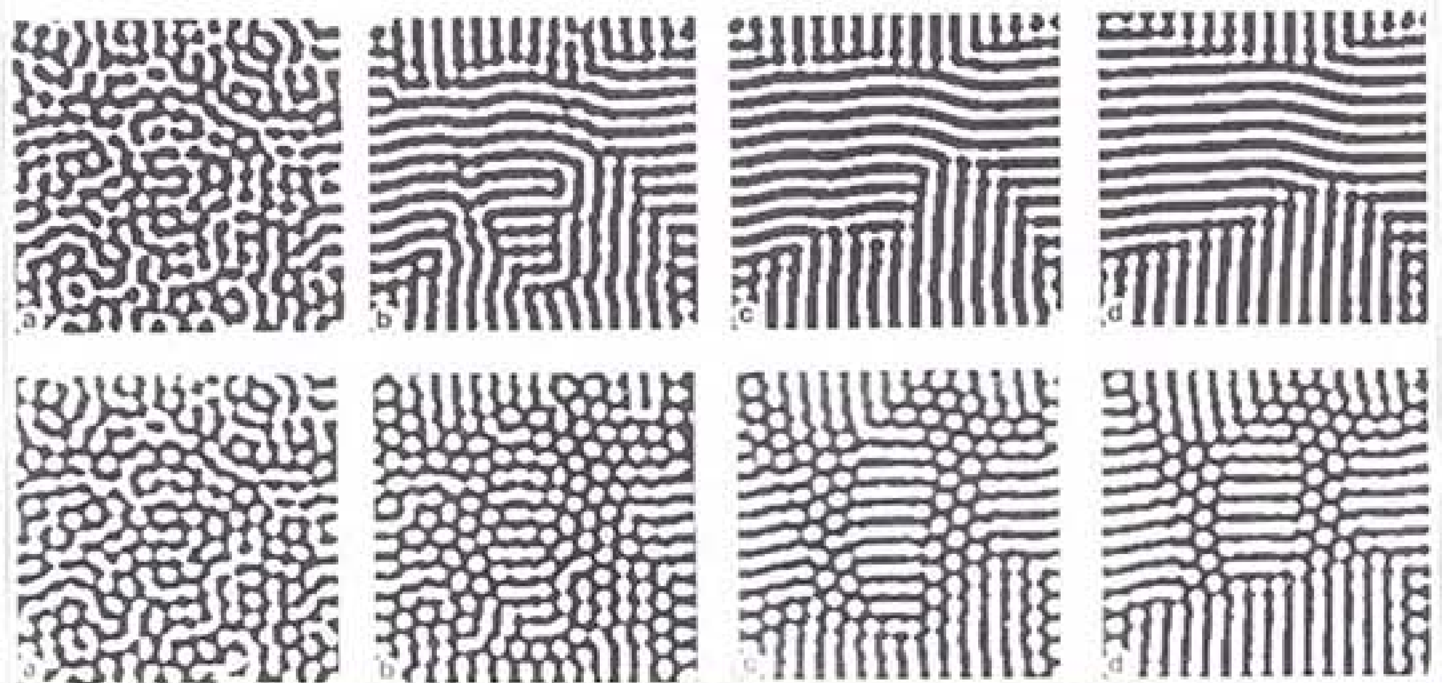
But the *Tonustal* remains a conductive model. Though able to explain, if vaguely, why a single stimulus can result in a range of responses, it fails to address those strangely spontaneous, rhythmic activities that unfailingly suggest generative processes at play. In the 1930s, after an extensive comparative study of animal locomotion that produced two miles of tracings, the systems physiologist Erich von Holst identified a neural oscillator that he defined as a system effecting periodic behavior. Von Holst may be said to have done for the neural oscillator what

4a, 4b, 4c. A chemical clock
The term synergy describes the combined action of two or more elements resulting in an effect that none of the individual elements is capable of achieving independently. Synergetic phenomena include the effects of different drugs in combination and the metallurgic performance of alloys. Lab accounts of the Belousov-Zhabotinskii Reaction, a type of chemical clock shown here, tell of a group of scientists standing around a petri dish scratching their beards. A tiny hair particle falls into the chemical solution triggering the characteristic pulsing spirals on the agitated surface. The B-Z reaction is a collective exchange of information by a myriad of individual chemical molecules. The rhythmic patterning that ensues is a real-time display of this coordinative process.

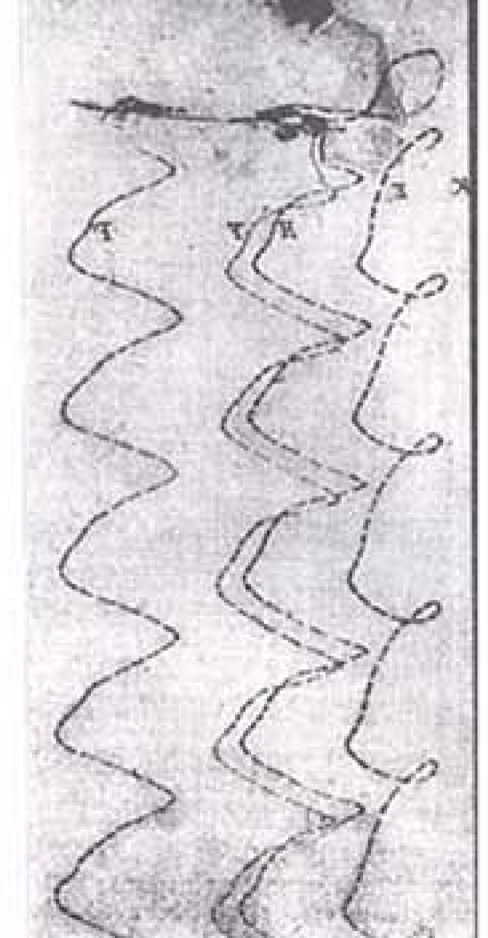


5a, 5b. Coupled oscillators in cockroach locomotion
An artificial neural network or ANN using coupled oscillators generates a cellular code that simulates a system of six-legged locomotion. Fourteen steps in the morphology of the computer code, are shown here.

6. Schooling Jacks
A school of hundreds of fish spontaneously transforms into a coherent defensive spiral. **This sensitive macro-organism responds collectively to stimuli, including even the slightest variations in water pressure that signals the orientation and proximity each individual fish. The transitory whale-scale shape persists just long enough to scare off potential predators.**



7a, 7b. Mathematics: the science of pattern
The systematic construction of new patterns is the business of math, where every equation or set of equations defines a distinct class of patterns. Individual patterns are realized as we substitute definite values for each of the equation's variables. Shown here is a graphic representation of the onset of turbulence in a vibrating liquid. In this example, two different variables are plugged into the same equation and from the same initial condition two divergent patterns develop.



9. Bernstein's kymocyclogram readout
In Bernstein's kymocyclogram readout (1923) the figure of a filing worker is seen overlayed with an indecipherable standard cyclogram of a single cycle of the same filing action. Below, a series of distinct curves shows the same movement, separated, this time photographed on moving film. K is a control bulb; E, the elbow joint; H, the wrist joint; F, the fingers of the right hand; and F¹, the fingers of the left hand. Frequency is 73 frames per second. This analytic recording technique was a precursor to Bernstein's three-dimensional stereoscopic imaging apparatus.

Sherrington did for the reflex. Examining the multiple ways in which the *Labus*, a fish that swims using rhythmic fin motions while keeping its body immobile, synchronized its fin movements, he arrived at two basic principles that characterize the coordinative properties of oscillators: the *Beharrungstendenz* and the *Magneteffect*. *Beharrungstendenz*, or the tendency of an oscillator to maintain its rhythm, leads to totally synchronized movements like chewing, breathing, and running, which von Holst referred to as states of absolute coordination. These steady, rhythmic oscillations work in clear contrast to the *Magneteffect*, which is the effect one oscillator exercises over another of different frequency so that it seems magnetically to draw and couple it to its own frequency. Phase slippages and temporal drifts, the outcome of a latent and perpetual struggle between *Beharrungstendenz* and *Magneteffect*, render infinitely variable couplings, easily forming larger compositions with smoothly altering tempos. Accelerated and decelerated running are states of relative coordination. Plastic forms such as dance are also manifestations of this phenomenon where oscillatory motions combine, forming molar ensembles moving fluidly from one mode to another. Sherrington's reflex arc intervenes here as an adaptive agent in these fields of oscillators. By introducing information from the outside into this highly tuned but otherwise hermetic ensemble, the reflex arc sensitizes ensuing activities to changing conditions in the environment.

Coordination is clearly plastic, variable, and adaptive, a versatile tilting of many scales of activity in space and time. Neural oscillators are the second elementary unit of a nervous system. Coupled oscillators are prototypes of a time-dependent nervous geometry.

EXCITABLE MEDIA

A nervous system is a matrix in a state of sustained expectation or excitation. Neural processes never cease. What we recognize as physical action – swinging a tennis racquet or swatting a fly – is but one aspect, the visible, external expression of an endless series of internal processes that remain invisible to us. The system never sleeps. One must resist all forms of analysis that attempt to characterize it as a collection of discrete parts, for a nervous system is a system that functions only as a whole. An action in one part of an organism is always accompanied by a definite, if imperceptible, change and compensation in the rest of the organism.[2] The reason we don't fall over the instant we lift one foot off the ground is because myriad signals literally cascade through the body to adjust and compensate for the shifted center of gravity. Such activities happen continuously and for the most part unconsciously. The manifest action of lifting a foot stands in the foreground of a flurry of background activities coursing through the body. Both foreground and background screens form a continuous surface, inseparable synergetic components of a single and same action. They form what is called a reaction gestalt, a global form that incorporates the entire body.

The relationship of figure and ground – or more precisely, manifest figure and subtending field, in which the background is not a fixed and consistent substrate but rather an infinitely flexible neural net – is critical to what I generically call any nervous system. In the geometry of a nervous system, figure and field do not oppose one another. A mutual, simultaneous, synergetic development of both always occurs.

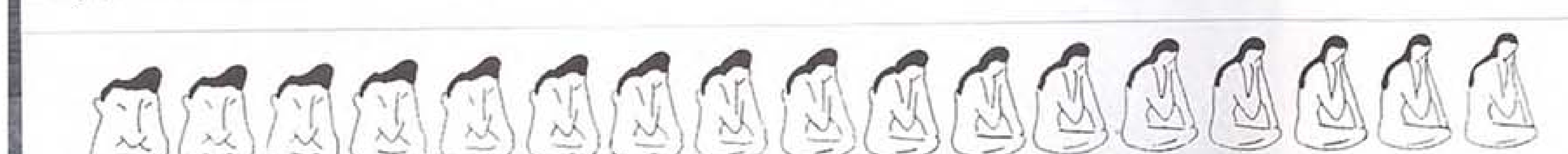
Imagine that the tip of your nose begins to itch. Itch stimuli emanating in the nasal tissue are transmitted to diverse regions of the nervous system. All anatomical regions to which these impulses are rapidly and repetitively fired are multiply interconnected by a network of neural components that endlessly configure and reconfigure themselves. Many duplicate representations of the same itch phenomenon are thus formed. These redundant, multiple representations create what is known as a *pattern of enervation* out of which a specific course of action, a physical movement, is formed. Now the pattern itself does not prescribe the use of a particular group of anatomical parts. For instance, if one's hands are occupied one may try alleviating the itch by wriggling one's nose. If this doesn't work one may transfer the activity that occupies both hands to a single hand and use the other to scratch. Or, failing this, one may turn one's head, and while tilting it sideways, try to rub the nose by raising and rotating the shoulder. Even if one never finally reaches the itch, the act of trying actually helps by discharging some of the excitation. Each attempt is not a separate action but rather part of a sequence of events – some occurring simultaneously – that unfolds smoothly and rapidly in time.

One way to think of this is to consider the processes involved in the production of holography: two-dimensional light diffraction patterns are inscribed by lasers on a photosensitive surface from which three-dimensional, dynamic holographic images are projected in space. Again the encoded, data-rich, nested patterns are continuously generated by a nervous geometry – potentially all forms of movement that could ultimately be expressed in the world as complex routines occurring in time and space.

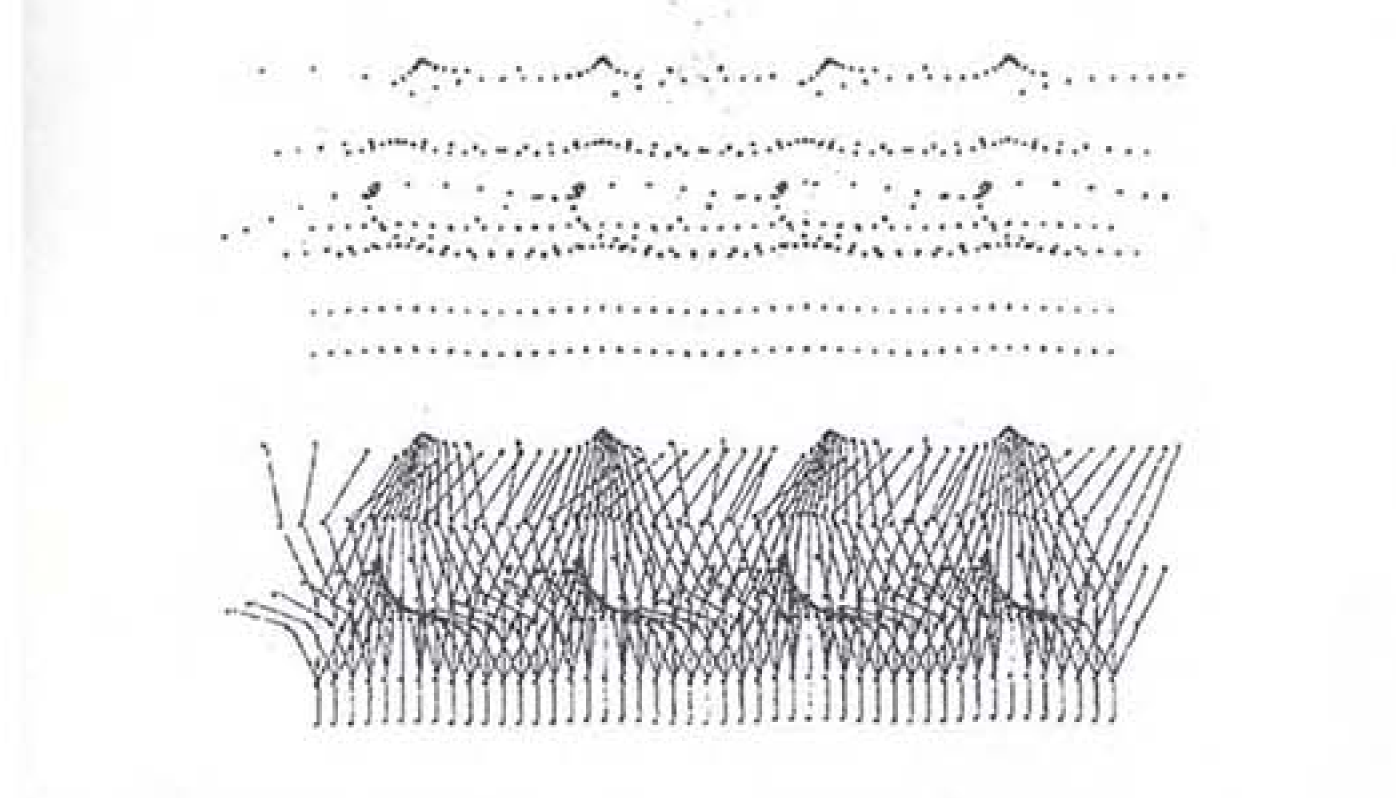
In short, *there is no master plan for action*. The spatiotemporal relationships of behavior and activity emerge incrementally. Their planning is *indefinite*. The kinematic details of coordinated activity – what parts move where and when – are not predetermined. They are not established in advance by a central command. Instead, enervation patterns operate in a general neural economy and are interpreted by any number of anatomical combinations employing a variety of neural pathways to achieve the anticipated effect – a specific movement.

ORGANIZATION OF ACTION

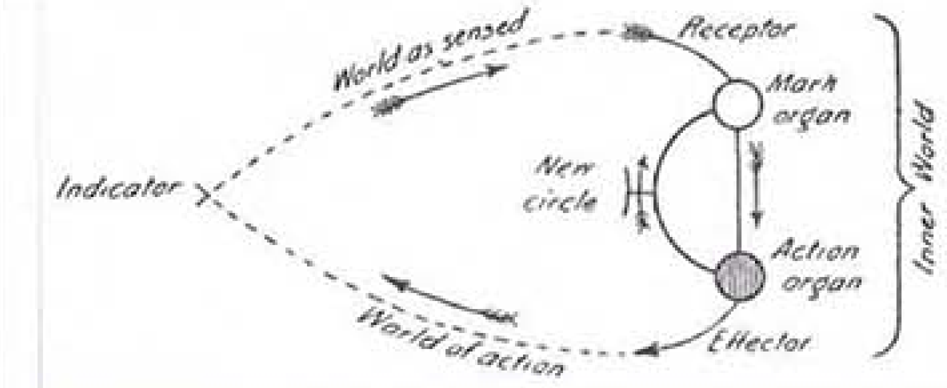
For the great Russian physiologist Nikolai Aleksandrovich Bernstein (1896–1966), whose work on neurological functioning was for decades buried by the Stalin-Lysenko regime, the problem of studying coordinate activity was one of understanding the control mechanisms of a complex kinematic apparatus. The turn of the century saw significant innovation in registration and recording technologies including chronophotography and cyclography, increasingly used to analyze physiological movement. Étienne-Jules Marey moved very quickly from an analysis of the motor functioning of physiological units (muscular activity, nerve impulses, cardiac rhythms, and so on) to a comprehensive chronicling of complex, visible, sequenced phenomena occurring in three-dimensional space. Relying upon his newly developed planar projection techniques Marey revealed the global or gestalt patterns formed by sequences of repetitive movements, such as walking and jumping, occurring in a variety of familiar social and biological scenarios.



8. Measuring ambiguity
This man-woman reversible figure, is an example of stochastic resonance. **When read from left to right and then back again from right to left, the point of transition from man to woman or woman to man occurs at different moments in the sequence. One way of understanding this trick of perception is that stochastic or irregular and periodic or regular forces combine in a noisy bistable system that produces two equally coherent but different sequences.**



10. The Synergetic computer
According to Alan Turing (better known for his role in the development of digital computers than for his critical work in morphology, that is, the developmental patterns of biological systems), most of an organism most of the time is developing from one pattern to another and not from homogeneity into pattern. Physiological processes always show patterns of constancy and change. Herman Haken's synergetic computer **is presented with a series of point light displays. The computer then "connects the dots" and identifies or recognizes the pattern correctly as walking. Pattern recognition replaces logic as the criterion used for defining and understanding complex interactive behaviors.**

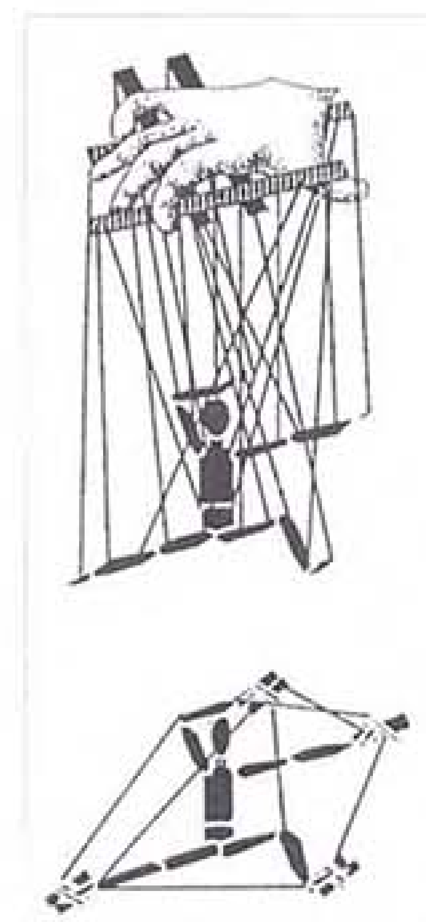


12. Sense-action cycle
An organism and its environment evolve as a composite dynamical system out of which patterns of constancy and change arise. In 1926, Von Uexküll diagrammed this interactive relationship.

In "The Techniques of the Study of Movement" published in *Textbook of the Physiology of Work* (1934), Bernstein surveyed the work of Marey as well as Eadweard Muybridge and others as an introduction to his own research, which relied on the precise recording of the movements of industrial production. Registration of activities such as filing and hammering, ubiquitous in machine-age processes, posed problems because, unlike the linear motion sequences chosen by Marey and Muybridge, the movements produced by a body at work were in large part cyclical and overlapping. The chronophotographic and cyclographic imaging of these movements yielded indecipherable tangles of lines. By means of kymocyclography, a technique developed by Bernstein in which a series of cyclographical exposures are registered on slowly and evenly moving photographic film, the tangled traces of simultaneous repetitive motions were resolved as a series of wavelike curves that could be read individually and in relation to one another. Precise relationships of moving parts could now be seen: a wrist, an elbow, a neck and head, and their associated muscles together constituting a compound action.

Quantifying the mechanics of the nervous system in Sherrington's mode, most physiologists of the time still understood the body as a reactive machine. For Bernstein, however, precision kymocyclographic imaging of body parts integrated and synchronized by a specific activity was the first step in understanding the criteria used by a nervous system in *producing* coordinated movement. Faced with the extreme redundancy of neural processing patterns, in what has become known as "The Degrees of Freedom Problem," he posed a crucial question: How does a nervous geometry effect an economy of means?

Bernstein's pioneering work surfaced in translation in the 1960s coinciding with the development of cognitive neuroscience. More recently it has motivated a burgeoning multidisciplinary field of research inspired by similarities between physiological coordination and other processes where multiple components become collectively regulated and self-organized.



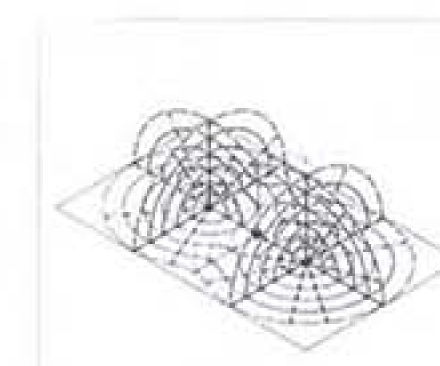
11. Degrees of freedom
The human body consists of 10^2 joints, 10^3 muscles, and 10^{14} cells. How are these very many degrees of freedom integrated? There are at least two ways of thinking about this. At one extreme there is the externally controlled marionette. In this formulation each individual anatomical unit behaves in a well-defined way according to outside instructions. At the other extreme, coordination can be considered as a process of self-organization, where there is no external direction. Participating parts cooperate in achieving a specific goal. The self-organizing marionette has fewer strings than the externally controlled puppet, for the same number of parts. Relationships between elements synchronize and therefore limit the marionette's many degrees of freedom.

SWARM

"*…neither a thing nor a concept, but a continual flux or process.*" – William Morton Wheeler, "Ant Colony as an Organism," 1911

Swarm, as a formalizable, mathematical entity owes its being to the synergy concept. A swarm is a network of distributed decision making: a real-time generator, processor, and integrator of stimulus-response patterns. A swarm takes form by integrating a multitude of individual performances. These performances are translated into patterned signals that permeate the swarm's entire field of operation. The signaling media and its means of transmission vary between one swarm aggregate and another. In economic markets, for instance, where endless data streams are instantaneously processed, prices transmitted via electronic networks are a form of feedbacksignaling that cues the activities of thousands of competitive agents. In insect colonies, on the other hand, all forms of cooperative interactive behavior (from foraging to nest building) are triggered by pheromones, hormonelike chemicals regulated by airborne gradients – not unlike the *Tonustäler* in von Uexküll's landscapes.

The idea of swarms as "superorganisms" or "collective brains" is hardly new, but the allusion misses the more interesting aspect of spontaneously organized apparatuses; from a matrix saturated with signal, interference, modulation, and cross talk – all of the stuff of communication – a single, albeit malleable form emerges, the one most likely to succeed in producing a particular global effect. If, as has been suggested by researchers, a swarm is in fact a model of a kind of brain, it is a brain whose cells are mixed in with the problem at hand. No single agent has a comprehensive overview of the entire field of activity – each depends on a continuous exchange of localized information. It is a form that persists because it constantly learns.



13. Geometry of pheromone flow fields
The nest-building performance of hundreds of thousands of African termites is coordinated by pheromones. Regulating chemical gradients directly effect the nest building procedure. The form of the nest is ultimately a result of the geometry of the pheromone flow fields shown above.

What now can be said about form? Since Fuller's so-called comprehensive design science, form can no longer, even in design disciplines, be said to be a *thing* but at the very least *a set of variable relations held in dynamic equilibrium*. Anticipatory design science consciously used nature as a model of successfully applied principles. It held that natural form was the physical record of *interrelated patterns of activity* occurring in time and space.

While design science certainly created the possibility for an entirely new framework for design, it could not but fail to reach its full potential within Fuller's rigid system where form was no more than the transparent demonstration of a static state of equilibrium. Once hyped as "the discovery of the coordinates of the universe," synergetics remained just that: another model of a coordinate system (the 90-degree Cartesian axis simply replaced by the 60-degree tetrahedron) not the transformative coordinating apparatus that Fuller sought.

The full force of Fuller's project can be understood as the attempt to develop an *integrative apparatus* possessing the capacity to establish *temporal* rather than mere physical stability. It is the rhythmic tiling of events in time that produces coherent form (witness von Holst's neural oscillators). Superseding the reactive neural system of the early 20th century, it is instead a complex *predictive nervous apparatus* capable of anticipating the physical and sensory consequences of a course of action that successfully integrates multiple processes in pursuit of a form for action.

1 … Handbuch der normalen und pathologischen Physiologie …

2 … The Organism: A Holistic Approach to Biology Derived from Pathological Data in Man …