Incorporations

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Nonorganic Life

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According to Thomas Kuhn's well-known theory, scientific revolutions are triggered by a "paradigm-induced gestalt switch." A traditional way of conducting scientific research is replaced by a new one (a new paradigm is implemented), and scientists come to perceive phenomena that previously were "invisible." Kuhn gives the Copernican revolution as one example of such a shift. Unlike Chinese astronomers, who had been able to observe the occurrence of sunspots centuries before Galileo simply because their cosmological beliefs did not preclude celestial change, early Western astronomers were unable to "see" changes in the cosmos. Sunspots, for example, remained "invisible" — that is, insignificant and anomalous — until Copernicus's ideas changed the ways in which European astronomers could look at the heavens.[1]

The last thirty years have witnessed a similar paradigm shift in scientific research. In particular, a centuries-old devotion to "conservative systems" (physical systems that, for all practical purposes, are isolated from their surroundings) is giving way to the realization that most systems in nature are subject to flows of matter and energy that continuously move through them. This apparently simple paradigm switch is, in turn, allowing us to discern phenomena that, a few decades ago, were, if they were noticed at all, dismissed as anomalies.

For example, when we approach systems as if they were conservative — that is, artificially isolate them (experimentally or analytically) from ambient fluxes of energy and matter — we are led to expect that these systems will eventually reach a point of steady-state equilibrium. However, when we acknowledge that these fluxes necessarily flow through the system, a new possibility emerges — a *dynamic* equilibrium. One of the most striking examples of this is the spontaneous assembly of a "chemical clock." In a "normal" chemical reaction, the interacting molecules simply collide randomly, transforming one another when the energy generated by their collisions passes a certain threshold. If we imagine the substances involved as, say, "red" and "blue," we

Another class of self-organizing phenomena, very different from those just discussed but also instrumental in reshaping how we understand the richness of expression of the material world, is called "solitary waves." Differing from ordinary waves in that they do not quickly dissipate as they move, they maintain their shape for a relatively long period of time. When, as happens, a solitary wave maintains its exact identity after interacting with other waves, it becomes a "soliton."[8] As with chemical oscillations, various forms of this phenomenon have been observed for a long time — over a century and a half — but they were relegated to the realm of anomalies. The first person to study these phenomena was John Scott Russell, a Scottish engineer and ship designer. In 1834, he witnessed the spontaneous emergence of a soliton in the surface of a canal near Edinburgh, and after chasing the coherent mass of water for several miles, he became convinced he had seen something extremely important. But science was not ready for this discovery, even though a mathematical explanation for it was available as early as 1892 (the Kortweg–de Vries equation).[9] As the components of a new scientific paradigm began to consolidate in the 1960s, solitons were recognized everywhere. In the ocean, for instance, they are called "tsunamis":

> Tsunamis are formed when a strong seismic shock occurs in the ocean floor. The wave, only a few inches or feet high, can travel intact across the ocean for many thousands of miles.... The human problem begins when the tsunami reaches the continental shelf. In shallower waters, nonlinear effects at the sea bed act to shorten the wavelength of the wave and increase its height. The result is awesome. From a soliton a few inches or feet high, the tsunami becomes a 100-foot mountain of water crashing into coasts and harbors. The tsunami that killed thousands in Lisbon in 1775 caused many writers in the age of Enlightenment to question the existence of a benevolent God. In 1702 a tsunami in Japan drowned over 100,000 people, and in the seismic soliton created by the volcanic explosion of Krakatoa Island in 1882 thousands died.[10]

Solitons can occur at much greater scales than tsunamis. In the atmosphere of Jupiter, for instance, there exists a soliton (the famous Red Eye) with a diameter roughly equal to the distance from the Earth to the Moon. On the other hand, solitons have also been found at extremely small scales: for example, this is the way in which electrons traveling through solid objects form charge-density waves. Indeed, *anything* that flows in regular waves (electricity, sound, heat, light) can give rise to solitons. Not surprisingly, the laws of classical thermodynamics would seem to forbid such coherent waves from arising spontaneously: if a given amount of energy is introduced into a flowing medium, the energy should diffuse evenly throughout the components of the medium. And indeed, this *does* normally happen; but in special circumstances, the energy can form into a pulselike wave and retain its

Zinc oxide smoke.

coherent identity over time — and in some cases, even after collisions with other solitons.

Chemical clocks (periodic and chaotic) and solitons exist within our bodies. An important chemical reaction in our own metabolism, which serves to transform glucose into useful energy (glycolysis), has been shown to generate spontaneously rhythmic oscillations.[11] Chaotic oscillations, on the other hand, occur in neural activity associated with the control of the heartbeat and the secretion of some hormones. (Apparently, nonperiodic oscillations are more adaptable and flexible than rigidly periodic ones, lending them, perhaps, a functional advantage.[12]) Solitons, for their part, are helpful in understanding how energy is conveyed throughout the human body: since regular waves dissipate their energy too rapidly to be of any metabolic use, coherent pulses that maintain their identity could explain how energy produced in one part of the body fuels processes in another, distant part. Solitons traveling along the "backbone" of certain proteins could be the answer to this puzzle.[13] Similarly, electrical signals travel through the nervous system too fast to be accounted for by the traditional understanding of "incoherent" waves; thus, solitons have been proposed as the most likely mechanism for neural signal transmission, and in this regard they have been described as constituting the "elementary particles of thought."[14] In short, it seems that our bodies are inhabited as much by the phenomena of "nonorganic life" as by the more familiar phenomena of organic life.

Chaos and solitons have become the yin and yang of the new physics.[15] At one extreme, there are relatively simple systems (a chemical clock, a mechanical pendulum), which can generate bewilderingly complex behavior; at the other, there are extremely complicated systems (oceanic and atmospheric motion), which can generate simple and coherent structures (pulselike solitons, or more generally, fronts, shock waves and bubbles). When the two are combined — by adding "friction" to a soliton-bearing equation, for instance — the result is the formation and competition of spatial patterns of great complexity and beauty. Indeed, what the study of chaos and solitons was to the 1980s, the study of pattern formation may be to the 1990s.[16] What is important for our purposes, though, is that both periodic and nonperiodic oscillations and coherent structures are among the unexpected possible behaviors of "inert" matter, behaviors of which we have only recently become aware. Matter, it turns out, can "express" itself in complex and creative ways, and our awareness of this must be incorporated into any future materialist philosophy.

One may well wonder why it has taken so long for these material effects to be recognized. Of the many possible explanations, one undoubtedly deserves special mention: our "mathematical technology" was simply incapable of modeling self-organizing phenomena. The kind

of equation most abundant in science (both classical and quantum), the "linear" equation, is extremely useful for modeling physical systems — not so much because this mathematical form captures all the relevant aspects of behavior, but because it provides a workable approximation, easily solved, and thus adequate in its predictive ability. Nonlinear equations, on the other hand, were not so easily solved, at least not before the advent of digital computers; even if they gave us a more realistic representation of reality, they were useless for practical applications. As a result, nonlinearities (like friction and air drag) were eliminated as much as possible from mathematical models, making nonlinear effects like chaos and solitons "invisible" (that is, visible only as anomalies to be eliminated). According to one mathematician:

> So docile are linear equations, that classical mathematicians were willing to compromise their physics to get them. [Consequently,] the classical theory deals with shallow waves, low-amplitude vibrations, small temperature gradients [that is, eliminates nonlinearities]. So ingrained became the linear habit that by the 1940's and 1950's many scientists and engineers knew little else.... Linearity is a trap. The behaviour of linear equations...is far from typical [in nature]. But if you decide that only linear equations are worth thinking about, self-censorship sets in.... Your textbooks fill with triumphs of linear analysis, its failures buried so deep that the graves go unmarked and the existence of the graves goes unremarked.[17]

Thus, one of the main causes of the paradigm shift that has allowed us to "see" matter as capable of self-organization is an advance in the technology that materially supports mathematics, and with it mathematical technology. Needless to say, this will not be an overnight replacement, and much of science (classical and quantum) will remain linear. But nonlinear science has begun to reveal new and startling facts about matter, in particular, that the behavior of entirely different material systems can exhibit "universal features." Physicists, for example, have known for some time that phase transitions in matter (from liquid to solid, from magnetic to nonmagnetic, from conductor to superconductor) display a common mathematical structure despite the diversity of their actual physical mechanisms. More recently, it was found that the onset of turbulence in a flowing liquid (a self-organizing process) is also closely related to such phase transitions, as well as to the onset of coherence in laser light. In a very important sense, then, all these transitions may be said to be "mechanism independent": one and the same "mathematical mechanism" can account for all these events that would seem otherwise to be wholly unrelated.[18]

Similarly, the onset of rhythmic behavior in a chemical reaction is identical to many other processes in which equilibrium systems suddenly begin to oscillate — a well-documented example is the spontaneous aggregation of slime mold amoebas, in which one individual amoeba

functions as a "clock" that regulates the assembly of other separate cells into one large multicellular organism. Nonlinear oscillations have been observed in fields as diverse as electronics, economics and ecological relations (such as predator–prey systems). Soliton phenomena, as we saw, occur at every scale, from Jupiter's Red Eye to tsunamis, to atomic charge-density waves, and in every kind of energy flow (heat, light, sound). This startling universality of the mathematics of self-organization is one of the most revolutionary elements of these new theories:

> "There is no better, there is no more open door by which you can enter into the study of natural philosophy," Michael Faraday has written, "than by considering the physical phenomena of a candle." Although the wisdom of this remark lay unrecognized for well over a century, it is now rather widely understood that the study of nonlinear diffusion in a candle... is closely related to the dynamics of nerve impulse propagation, the spread of contagious disease, and the beating of the human heart.... The same equation that solid state physicists and electrical engineers use to describe the propagation of magnetic flux quanta (called "fluxons")... is also employed by theoretical physicists as a model for elementary particles. Similarly, the soliton on an optical fibre... is closely related to suggested mechanisms for the transport and storage of biological energy in protein.[19]

In mathematical terminology, the events at the onset of self-organization are called "bifurcations." Bifurcations are mutations that occur at critical points in the "balance of power" between physical forces — temperature, pressure, speed and so on — when new configurations become energetically possible, and matter spontaneously adopts them. It is as though "inert" matter, confronted with a problem stated in terms of a balance of forces, spontaneously generates a machinelike solution by drawing from a "reservoir" of abstract mathematical mechanisms. For instance, in the case of chemical self-organization, two distinct forces are at work: the rate at which the substances diffuse and the rate at which they react with each other. When the balance of power is dominated by diffusion, the result is a steady-state equilibrium, but the moment reaction rates begin to dominate, the chemical substances are suddenly confronted with a new problem, and they must respond to the challenge by adopting a configuration that meets the new energetic requirements. In this case, the new stable solution to the problem is to enter into an oscillatory equilibrium, and it is in this way that chemical clocks are born. But, again, more important than the self-assembly of these clocks is the fact that essentially the same solution is available to other systems, like populations of electronic circuits or of economic agents, which involve balances of power between forces of a completely different kind.

Gilles Deleuze and Félix Guattari have suggested that this abstract reservoir of machinelike solutions, common to physical systems as

diverse as clouds, flames, rivers and even the phylogenetic lineages of living creatures, be called the "machinic phylum"[20] — a term that would indicate how nonlinear flows of matter and energy spontaneously generate machinelike assemblages when internal or external pressures reach a critical level, which only a very few abstract mechanisms can account for. In short, there is a single machinic phylum for all the different living and nonliving phylogenetic lineages.

The machinic phylum remained largely invisible until the advent of digital computers; or rather, considering how pervasive nonlinear behavior is throughout nature (it could hardly have escaped everyone's attention), we had to learn to recognize it.[21] Bifurcating sequences leading to complex behavior *had* been "observed" by mathematicians such as Henri Poincaré as early as the 1890s — although those early glimpses into the wild spaces of the machinic phylum horrified most who saw them. Those passing glimpses have, with the proliferation of computers in mathematical investigations (giving rise to "experimental mathematics"), opened onto vast landscapes — computer screens becoming our "windows" onto the machinic phylum in more than a figurative sense.

If computers have emerged as windows onto this world, it is because the nonlinear mathematical models of bifurcation processes can be given a visual representation, a "phase portrait." The first step in creating a phase portrait is to identify the relevant aspects of the behavior of the physical system to be modeled. It is impossible, for example, to model an oven by considering each and every atom of which it is composed, but one *can* consider the single aspect of the oven that matters: its temperature. Similarly, in modeling the behavior of a pendulum, only its velocity and position are important. In technical terms, the oven has "one degree of freedom," its change in temperature; the pendulum, in turn, has two degrees of freedom. A bicycle, on the other hand — taking into account the coordinated motion of its different parts (handlebars, front and back wheels, right and left pedals) — is a system with approximately ten degrees of freedom.

The next step is to create an abstract space (called "phase space") that has as many dimensions as the system to be modeled has degrees of freedom.[22] In this way, everything that matters about the system at any given moment in time can be condensed into a single point: a point in one-dimensional space (a line) for the oven, a point in two-dimensional space (a plane) for the pendulum or a point in ten-dimensional space for the bicycle. Moreover, as the system changes in time (the oven heats up or the bicycle makes a turn), this point in phase space will also change, thus describing a trajectory. This trajectory, in essence, will contain all the information that matters about the history of the modeled system. For example, if the system under study tends to oscillate between two extremes, like a driven pendulum, its trajectory in phase


Liquid crystals.

space will form a closed loop, which represents a system whose "movement" consists of a repetitive cycle. A free pendulum, on the other hand, which eventually comes to a standstill, appears in a phase portrait as a spiral. More complex systems will be represented by more complex trajectories in phase space.

Now, it is one thing to model a system with a set of equations, but quite another to solve those equations. Sometimes, when the equations modeling a system are so complex that they cannot be solved — that is, when they are nonlinear — scientists can nevertheless learn something about the system's behavior by looking at its phase portrait. They cannot make precise quantitative predictions about the system, but they can use the phase portrait to elicit qualitative insights about the general traits governing the system's long-term tendencies. In particular, there are certain special spots in phase space that tend to attract or repel all nearby trajectories; that is, regardless of where a trajectory begins, it will tend to drift toward certain points (called "attractors"), or to move away from certain others (called "repellors").

Because these trajectories represent the behavior of real physical systems, the attractors and repellors in a phase portrait represent the long-term tendencies of a system. For instance, a ball rolling downhill will always "seek" the lowest point. If it is pushed up a little, it will roll down to this lowest point again. Its phase portrait will contain a "point attractor": small fluctuations (the ball being pushed up a little) will move the trajectory (representing the ball) away from the attractor, but then the trajectory will naturally return to it. Other systems will have two point attractors or more. A well-made light switch, for example, whose resting states are "on" and "off," has two attractors — and if it is delicately set between them, chances are good that it will spontaneously snap into either position. Its phase portrait can't tell us *when* it will do so — that is, provide a precise quantitative prediction, which implies that the equation has been solved — but it can describe the system's long-term tendency to snap into one of its points of equilibrium. In fact, the specific form of the nonlinear equation modeling the system will reveal this before its specific trajectory has been calculated.

Attractors, though, do not necessarily appear as points. For example, an attractor with the shape of a closed loop (called a "periodic attractor" or "limit cycle") will force all trajectories passing nearby to wrap around it, to enter into an oscillating state, like a pendulum. If the phase portrait of a physical system has a periodic attractor embedded in it, we know that no matter how we manipulate the behavior of the system, it will tend toward an oscillation between two extremes.

These two attractors, points and closed loops, were the only types known before computer screens opened windows onto phase space. What followed was the discovery of a much wilder array of creatures

inhabiting phase space: among them were attractors with strangely tangled shapes, called "strange" or "chaotic" attractors, representing turbulent behavior in nature, and the incredibly complex, chaotic boundaries separating "basins of attraction" (a simple attractor's sphere of influence in phase space). Far more startling, though, was the discovery that an attractor can spontaneously mutate into a different attractor. These spontaneous transformations are known as "bifurcations." For instance, a physical system that originally tended toward a steady-state equilibrium (a point attractor) can suddenly begin to oscillate between two extremes (a limit cycle); this would describe the self-assembly of a chemical clock. Spontaneous self-organization can take other forms as well: the onset of turbulence in a flowing liquid appears in phase space as a cascade of bifurcations that takes a circle (limit cycle) and, through successive doublings, transforms it into a strange attractor. Roughly, we could say that phenomena of self-organization occur whenever a bifurcation takes place: when a new attractor appears on the phase portrait of a system, or when the system's attractors mutate in kind.

We have, then, three distinct entities inhabiting phase space: specific trajectories (corresponding to systems in the actual world), attractors (corresponding to the long-term tendencies of these systems) and bifurcation events (corresponding to the emergence in these systems of new structural tendencies). Bifurcation events are brought about by changes in certain "control parameters," which represent the more or less constant conditions affecting physical objects; temperature, pressure, gravity and so on. As the value of a parameter shifts through certain ranges, the attractors of the physical system represented will usually change subtly; at certain critical points, though, a bifurcation will take place, and the attractors will transform themselves.

As I said earlier, because essentially the same attractors and bifurcations are available for many different physical systems, they may be seen as *virtual* or *abstract mechanisms* that are "incarnated" in different concrete physical mechanisms. This is not to say that attractors and bifurcations exist in some platonic realm waiting to be realized — rather, *they are intrinsic features of the dynamics of physical systems, and they have no independent existence outside of those physical systems.* Yet, attractors and bifurcations do constitute an abstract reservoir of resources available to nonlinear flows of matter and energy — a condition that applies as much to the beating of hearts as to earthquakes, flames and clouds, tsunamis and amoebas. And it is in this respect that I introduce the term "machinic phylum" to designate a single phylogenetic line cutting through *all* matter, "living" or "nonliving," a single source of spontaneous order for all of reality. More specifically, the attractors define the more or less stable and permanent features of this reality (its long-term tendencies), and bifurcations constitute its source of creativity

and variability. Or to put it more philosophically, attractors are veritable "figures of destiny," for they define the future of many systems.

For instance, when the dynamics of a physical system are governed by a periodic attractor, it is as if the very flows of matter and energy rushing through the system were binding it, or destining it, to an oscillatory future. And yet, for several reasons, this iron-clad determinism should not be given too mechanistic an interpretation. For one thing, the phase portraits of most systems usually contain more than one attractor, which means that the system in question has a "choice" between several destinies. Then, there is the "freedom" built in to chaotic attractors. When a system's dynamics are caught in a strange attractor (deterministic chaos), that system is "bound to be creative," that is, to explore all the possibilities of a small region of phase space. Furthermore, even if we are destined to follow the attractors guiding our dynamical behavior, there are also bifurcations, critical points at which we may be able to change our destiny (that is, modify our long-term tendencies). And because minuscule fluctuations in the environment in which a bifurcation occurs may decide the exact nature of the resulting attractors, one can hardly conclude that all actions we undertake — as individuals or collectively — are irrelevant in the face of these deterministic forces. Bifurcations may not be a "guarantee of freedom," but they certainly do provide a means of experimenting with — and perhaps even modifying — our destinies:

> From the physicist's point of view this involves a distinction between states of the system in which all individual initiative is doomed to insignificance on one hand, and on the other, bifurcation regions in which an individual, an idea, or a new behaviour can upset the global state. Even in those regions, amplification obviously does not occur with just any individual, idea, or behaviour, but only with those that are "dangerous" — that is, those that can exploit to their advantage the nonlinear relations guaranteeing the stability of the preceding regime. Thus we are led to conclude that the same nonlinearities may produce an order out of the chaos of elementary processes and still, under different circumstances, be responsible for the destruction of the same order, eventually producing a new coherence beyond another bifurcation.[23]

Although attractors and bifurcations appear *only* in the phase portraits of systems that are "dissipative" (those in which energy is not conserved), even conservative systems show a partitioning of phase space into regions, some of which define systemic long-term tendencies. Such a phase space may be seen as an "energy landscape," with peaks and valleys that correspond to maxima and minima of free energy. These valleys serve as attractors in the sense that these systems will spontaneously adopt a physical configuration that minimizes the amount of free energy — in other words, their trajectories will tend toward

interacting with one another. A *real* planet, on the other hand, has mountains, valleys and other geological formations. Were we to peer inside the mountains, for example, we would find folded layers of different types of stone. In short, we would observe a historical structure — *not* a collage of states of matter.

On Earth, the main historical process responsible for the formation of mountains and other structures, is called the "geological cycle." Briefly put: Erosion and weathering create the raw materials for the cycle (stones, pebbles, grains), which rivers, through a process known as "hydraulic sorting," sort out and deposit as sediment at the bottom of the ocean. The sediment already has a structure, since the sorting process causes matter to deposit in distinct layers. When these layers are buried under further deposits, they undergo a transformation: the pebbles and grains that form these layers are cemented together into sedimentary rock (for example, sandstone or limestone). When these rock layers are folded under the pressure of movements of the Earth's crust, mountains emerge — which are then sculpted by erosion, and so on ad infinitum.[30]

Self-organizing processes drive the geological cycle. The tectonic forces behind the burial and folding of sediment are driven by molten rock flowing up from beneath the crust in convection cells, a coherent flow arising after a temperature bifurcation, constituting a kind of self-assembled conveyor belt. The rivers that sort out the pebbles and grains that make up the layers of sediment, can be seen as self-organized "hydraulic computers." The dynamics of a river's flow at different points in its course are governed by different attractors, turbulent flow from strange attractors, and coherent pulses (solitons) from weaker forms of nonlinear stabilization. It is these different "regimes of flow" that give the river its capability of sorting raw materials by grain size, shape and even composition.[31] Finally, the processes of erosion and weathering also act as "filters" or "sieves," sorting out materials by their degree of stability. Mountains are worked over by these processes, removing those components that are not fully stable, and leaving behind those that are strongly locked into their attractors. (For this reason, granite, a highly stable crystalline configuration, is typically found on high ground.[32])

Thus, adding these historical processes changes our simple picture of the birth of a planet. Instead of a simple sequence of bifurcations taking us from a plasma to crystal, here the formation of hardened structures involves attractors and bifurcations engaged in more complex interactions. The self-organized machinic assemblages they create (conveyor belts, hydraulic computers) provide the labor needed to generate geological constructions in a two-step process: first, the raw materials are selected and sorted (sedimentation), then they are consolidated

into permanent structures (cementation or hardening). Because the end result of these two operations is geological strata, this process of double articulation has been given the name of "stratification."[33]

According to Deleuze and Guattari, processes of stratification occur not only in the world of geology but in every sphere of reality. In other words, any sphere of reality — the hydrosphere, the biosphere and so on — can be defined in terms of flows of matter and energy and the reservoirs driving those flows. At any given point in time, portions of these flows will be involved in any number of actively self-organizing processes; other portions of the flows, however, will have sedimented or hardened into more or less stable structures. Thus, we can describe a given region of the planet at a given moment by specifying which of the three possible states of these flows predominates: freely self-organizing, loosely bound or rigidly bound. But because these states are neither irreversible nor exclusive, we can speak of various components in terms of the "degrees of stratification" they exhibit.

For instance, a rock may seem to us the archetypal example of permanence and stability, but when one takes the long view, even *rocks* flow: their atoms migrate along grain borders (self-diffusion), dislocation boundaries within grains move, cracks and fissures propagate. In this sense, the flow of rocks is very viscous; they constantly change, but at extremely slow speeds. Furthermore, under extreme heat and pressure, rocks may undergo a bifurcation (limestone, a sedimentary rock, metamorphoses into marble).[34] Alternatively, rock may be melted into lava and reincorporated into the convection flows driving plate tectonics. Stratification, then, is in no way a terminal state: free matter and energy stratify, and the stratified destratifies.

Moreover, hydrological strata (rain belts, ice caps, rivers), atmospheric strata (pressure systems, wind patterns) and organic strata (food chains, dominance hierarchies) can also be understood as complexes of matter and energy flows that are stratified to different degrees.

What we have, then, is a kind of "wisdom of the rocks," a way of listening to a creative, expressive flow of matter for guidance on how to work with our own organic strata.[35]

Organic stratification, which gives rise to our own bodies (among other things), unfolds through chemical reactivity — that is, the onset of a reaction transforming one set of substances into another. This, too, can be considered a phase transition because these reactions involve "activation thresholds," the minimum amounts of energy necessary for chemical processes to begin. The control parameters determining these processes, however, are by no means fixed: catalysts — substances capable of manipulating these activation thresholds without themselves

being affected — can raise the thresholds or lower them, and in this way can either inhibit or enhance a reaction.

In a very literal sense, catalysts are the first form of matter that can affect directly the control parameters driving bifurcations, either preventing or accelerating their actualization. (More precisely, catalysts push systems away from their attractors and toward the border of their basin of attraction, where small fluctuations can push them into the domain of a different attraction.[36]) In some cases, a substance can catalyze its own production (autocatalysis); in others, two or more substances can "cooperate" with one another by catalyzing each other's reactions (cross-catalysis). Chemical clocks arise only in these kinds of reactions. Among all the elements, the most powerful catalysts are metals, and for this reason metals have been said to bear a privileged status in the machinic phylum:

> [W]hat metal and metallurgy bring to light is a life proper to matter, a vital state of matter as such, a material vitalism that doubtless exists everywhere but is ordinarily hidden or covered, rendered unrecognizable.... [M]etal is coextensive with the whole of matter, and the whole of matter to metallurgy. Even the waters, the grasses and varieties of wood, the animals are populated by salts or mineral elements. Not everything is metal, but metal is everywhere. Metal is the conductor of all matter. The machinic phylum is metallurgical, or at least has a metallic head, as its itinerant probe-head or guidance device.[37]

This special capability of catalysts to intervene in the dynamics of other processes is the necessary precondition for life to begin. Indeed, the catalysts involved in living processes, called "enzymes," are far more specific than metals in their dynamic effects, allowing for much more detailed control of chemical reactions. The instructions for building each enzyme are stored in DNA, and this allows particular enzyme "designs" to be not only inheritable, but also capable of being fine-tuned for specific functions through the action of natural selection. Because the translation of sequences of DNA into enzymes is itself an activity regulated by enzymes, we seem to have here a classic chicken-or-egg dilemma.

Recent theories of how a machine as complicated as DNA and its translation operations came to be assembled begin with networks of cooperating nucleic acids and enzymes. One suggested precursor, called a "hypercycle," might have been a self-replicating molecule (nucleic acid) coded to produce an enzyme that enhanced the production of a second nucleic acid, which, in turn, coded for an enzyme that enhanced the production of the first — a dynamical cross-catalytic system governed by attractors and subject to bifurcations.[38]

Such a cooperating network might have been the mechanism through which the machinic phylum gave rise to organic life. Organic

Cathode-ray ocilloscope pattern.

strata, however, differ from geological strata in that they have enveloped within their sphere of operations the control parameters driving bifurcations. In the case of our hypothetical crystal planet, the forces determining the control parameters (temperature, pressure, volume) had not yet been integrated into, nor harnessed by, the mountains and rocks they gave rise to. The latter simply emerged as the flows of matter and energy underwent bifurcations, but these structures had little or no effect on which bifurcations occurred. With organic strata, on the other hand, the stratified structures — in particular, DNA — also drive the control parameters, and are thereby able to determine which bifurcations are actualized.

For our purposes, we can treat living systems as made of two kinds of components: those that function more or less independently of the rate and flow of matter and energy, and those that depend critically on these rates of flow (that is, on degrees of viscosity or stratification). The bifurcations of the latter occur only at critical points in the rate of flow of matter and energy, whereas the instructions stored as genetic information for the assembly of enzymes are completely stratified and rate independent. In this sense, DNA and its enzymes can be seen as a complex parallel computer regulating the relative "viscosities" of different flows so as to permit the actualization of certain bifurcations but not others. This is, in essence, the hypothesis proposed by philosopher Howard Patee, who calls information-based structures like DNA "symbol systems":

> [S]ymbol systems exist as rate-independent (nonintegrable) constraints.... [They do not] depend, within wide limits, on the rate of reading or writing, or on the rate of energy or matter flow in the symbol-manipulating hardware. On the other hand, the effect...of symbols functioning as instructions is exerted through the selective control of rates. For example, the rate of reading or translating a gene does not affect the determination of which protein is produced. However, the synthesis of the protein as instructed by the gene is accomplished through the selective control, by enzymes, of the rates of individual reactions.[39]

These separate roles played by DNA and nonlinear, self-organizing processes can perhaps be best illustrated by looking at the way in which the genetic information contained in a fertilized egg is slowly converted into a fully developed individual of a given species. This is the process known as "embryogenesis." Roughly speaking, during embryogenesis two kinds of processes occur: those mediated by DNA, thus subject to genetic control, and those governed by attractors and bifurcations, thus constrained but not created by genetic information.

An egg consists of a nucleus (containing genetic information) and cytoplasm. Traditionally, the latter was regarded simply as a source of energy and nutrients for the developing embryo, but it is now known

to play a much more fundamental role. As a rule of thumb, we should look for manifestations of nonorganic life in those processes in the developing embryo where the nucleus is not involved *as a source of informational constraints*. This qualification is necessary because the nucleus may be involved in the emergence of bifurcations, though not by virtue of its genetic material. For example, its position in the egg can create an initial "polarity" between different zones of the egg. This initial polarity, established during the formation of the egg (oogenesis), has been found to constitute a fundamental source of asymmetry guiding the development of the first few stages in embryogenesis. Even when the genetic activity of the nucleus has been inhibited, an egg will undergo certain early bifurcations due to its global dynamics:

> Self-assembly during [the early stages of] embryonic development is not mediated by direct gene intervention. When all the transcriptions have been prevented [through the use of an inhibitor] the regular cleavage patterns are retained. However, the polarity of molecular organization of both the egg's cytoplasm and its nucleus (chromatic) are essential for normal development. Hence the main features of [early] embryogenesis — cell differentiation, induction, determination of pattern formation — all stem from the oogenetically originated, spatial distribution of preformed informational macromolecules. The initial condition of embryogenesis is oogenesis. The epigenetics of embryonic development is built on the topological self-organization and orientation of macromolecules of the total egg.[40]

In later stages of embryo development, the emergence of the patterns forming various organs and structures — an eye, a leg and so on — similarly involves events directly mediated by DNA and those resulting from the global dynamics of interacting cells. Historically, the study of embryogenesis has shifted in the importance attributed to each of these factors. A century ago, there were two main theories of embryogenesis: one positing that organs are somehow preformed in the egg, and another positing that organs arise out of the dynamics of development. The first approach held that, as an egg cell divides, each cell would contain half of the total organism and so on throughout the course of embryogenesis. This has, of course, been proven false, for the destiny of a cell is not rigidly predetermined but, rather, is *regulated* during development:

> The classical demonstration of [the phenomenon of regulation] was provided in the 1890s in H. Driesch's experiments on sea-urchin embryos. When one of the cells of a very young embryo at the two-celled stage was killed, the remaining cell gave rise not to half a sea-urchin, but to a small but complete sea-urchin. Similarly, small but complete organisms developed after the destruction of any one, two or three cells of embryos at the four-celled stage. Conversely, the fusion of two young sea-urchin embryos resulted in the development of one giant sea-urchin.[41]

Several hypotheses have been proposed to explain the regulation of cell differentiation, the process through which a group of essentially similar cells — for example, an egg after the first few divisions — gives rise to incredibly diverse tissues. Following the discovery of DNA, it was thought that differentiation was entirely genetic — that as cells differentiated, their DNA changed as well, guiding the development of various sets of proteins and enzymes for various cell types. It was found, however, that DNA remains essentially the same in cells of totally different types.

What, then, accounts for cell differentiation? One general hypothesis holds that during embryogenesis certain chemical patterns emerge and guide cells to produce specific proteins at specific times. There are, in fact, several theories about exactly how chemical patterns accomplish this task, which differ mainly in the importance they attribute to genetic information in the guidance of these processes. On the one hand, the "positional information" hypothesis asserts that simple gradients of chemical concentrations are interpreted by differentiating cells according to a very complex genetic code. On the other, the "prepattern" hypothesis asserts that chemical patterns are very complex, and the genetic code with which the cells interpret them is very simple.[42] Clearly, there is a trade-off here: the greater the complexity one attributes to a self-organizing chemical pattern, the less the genetic information one need postulate for its interpretation, and vice versa.

For a long time, the latter hypothesis was favored because a mechanism for spontaneously forming simple chemical patterns seemed much more likely than one for complex patterns. But, as I suggested at the beginning of this essay, this situation is changing rapidly: chemical reactions are now viewed as capable of undergoing several kinds of bifurcations that result in the self-assembling chemical clocks, traveling waves, spirals and other complex patterns previously thought impossible. So the hypothesis of a prepattern is becoming accepted more widely, and with it an increased role for nonorganic life in the creation of organic structures.[43]

Regulation and regeneration were what first prompted scientists to postulate forces in embryogenesis other than genetic information. At particular stages in the development of an embryo, groups of cells interact and thereby develop along specific paths. These paths, though, do not seem to be wholly determined by genetic control: if a group of cells in a developing embryo is transplanted from one region to another, they will develop, not into the structure emerging in the first area, but into the structure corresponding to the second. These stable paths of development that guide or "canalize" cell behavior have been called "chreods."[44] Confronted with such self-organizing phenomena, one scientist has felt the need to postulate the existence of physical forces unknown to ordinary physics, which are supposed to act in a nonenergetic way, independently of space and time.[45] I see no need, however,

for postulating mysterious agents to account for chreods: the attractors guiding the global dynamics of interacting cells suffice to account for their canalized behavior, and the bifurcations arising in those dynamical interactions adequately account for the emergence of the attractors themselves. More specifically, the enzymes produced by the expression of genetic information enter into "chemical reaction networks" whose dynamics are guided by attractors. Each type of cell (bone, muscle, nerve) is now thought to arise from a different attractor, with the DNA simply pushing cells from one basin of attraction to another.[46] This description has the advantage of explaining the spontaneous emergence of new patterns by invoking only intrinsic features of the global dynamics of cell populations, without postulating additional forces with mysterious properties.

Roughly speaking, then, the belief that all embryological events involve direct genetic supervision is giving way to a new vision: the egg begins as an undifferentiated field that undergoes a series of bifurcations, each of which produces a new set of attractors that form the chreods guiding development until the next bifurcation. One scheme for classifying attractors and bifurcations, known as "catastrophe theory," presents a taxonomy of seven elementary morphogenetic (that is, form-producing) events. To each of these sets of attractors and bifurcations corresponds a different process of self-organization in cell groups: in the right conditions, these will tend spontaneously to form a pleat or a fold, a pocket, a spike or a furrow.[47]

The more self-organizing processes scientists discover, the smaller the domain of DNA's control appears to be. Rather than including a complete blueprint for the construction of an entire individual, DNA must include only enough constraints to harness self-organizing processes in the creation of the structures that characterize a particular species. Mathematical analysis has established (for now) that the attractors and bifurcations guiding these dynamics are relatively few in number, so organic processes of stratification are themselves constrained by dynamical forces. In other words, morphogenesis — for example, the spontaneous emergence of form in a relatively formless egg — is limited by the available attractors and bifurcations. Hence, DNA constraints can only operate within these limits. In the words of one biologist:

> There are several consequences of this view of morphogenesis. First, it is evident that morphology is generated in a hierarchical manner, from simple to complex, as bifurcations result in spatially ordered asymmetries and periodicities, and non-linearities give rise to fine local detail. Since there is a limited set of simple broken symmetries and patterns that are possible (e.g., radial, bilateral, periodic), and since developing organisms must start off laying down these elements of spatial order, it follows that these basic forms will be most common among all species. On the other hand, the

Crystal of virus.

> finer details of pattern will be most variable between species, since the pattern-generating process results in a combinatorial richness of terminal detail, and specific gene products in different species stabilize trajectories leading to one or another of these.... The fact that virtually all the basic organismic body plans were discovered and established during an early evolutionary period, the Cambrian, is often remarked with surprise, but it is just what one would expect on the basis of the above argument. "Ancient" and "recent" morphological characters are secondary consequences of the hierarchical nature of morphogenesis and the exploration of its potential in time.[48]

The idea of an undifferentiated egg slowly developing into a full organism as it crosses bifurcations corresponds to our earlier image of a formless plasma giving rise to a crystal planet as it cools down and undergoes phase transitions. But as we saw before, we must also bring into play the action of historical processes of stratification in order to complete the picture. Like volcanoes in the lithosphere or hurricanes in the atmosphere, creatures in the biosphere must meet strict matter and energy budgets. The flow of flesh (biomass) through food chains constitutes the main form of energy circulation in organic strata — that is, energy budgets are met by all living creatures by eating and avoiding being eaten. In all ecosystems, planets are at the bottom of these food chains, constituting a reservoir of solar energy stored chemically (through photosynthesis). On top of this layer of primary productivity come several layers of consumers (herbivores, carnivores). The specific job that an animal or plant performs in an ecosystem (what is called its "niche") is defined by its position in one of these circuits for the circulation of biomass. So in this sense, organic strata are, like any other strata, composed of temporary coagulations of matter (the bodies of plants and animals), themselves the product of the ceaseless flow of energy through ecosystems.[49] And yet, animals and plants are unique in that they must also meet a second budget, a genetic budget that compels them to try to spread their genes as far and wide as possible. For these creatures, meeting their energy–matter budget is, in a sense, of secondary importance. They must eat and avoid being eaten only to endure until the mating season, when the main objective of their lives is revealed: the continuation of a genetic line, the preservation of the portion of the gene pool they encapsulate. The gene pool of a species may be seen as a veritable reservoir driving flows of genetic material through the bodies of its individual members. More specifically, a gene pool supplies the raw materials for the pruning process of natural selection. It contains the stored "experience" of the species over many generations, the "knowledge" of how to survive successfully in a given environment. Individual animals and plants are like temporary "experiments" with which gene pools probe current environmental conditions to make sure

that past successes are still viable (in other words, that energy–matter budgets can still be met as before).[50]

Although gene pools are designed to replicate themselves very accurately (and thereby preserve past experience intact) random copy-error (mutations) and sexual shuffling of gene groups (recombination) generate enough variation so that these genetic reservoirs can respond to new environmental challenges. In short, thanks to variation, gene pools can evolve and be submitted to historical processes of stratification. Roughly speaking, mutation and recombination play the role of erosion and weathering — that is, they provide the raw materials for the sorting process of natural selection. In the simplest case, for example in the case of selection by climatic conditions, this process merely sorts out the fit from the unfit, or more generally, the stable from the unstable. And yet, like the hydraulic computers mentioned above, selection pressures are also patterned by nonlinearities. For instance, some pressures may add some directionality to evolution, as in the case of natural arms races: a thickening of the armor in a prey species directly provokes a sharpening of the claws and teeth in its predatory counterpart, which in turn puts pressure on armor designs to get even thicker. Similar catalytic loops occur between parasites and hosts, or between male decorations and female sexual choice.[51] In other cases, when the fitness of a particular trait or behavior is nonlinear (that is, when selection pressures depend on how frequent that behavior is exhibited in a population), behavioral patterns come to be stabilized by attractors (the so-called evolutionary stable strategies).[52]

Thus, selection pressures of many kinds play the same role that processes of sedimentation perform in the case of rocks. They select the stable from the unstable, and then sort out what's left into the layers of a food chain. The analogy does not end there. Like patterns in the sedimentary deposits that form at the bottom of the ocean, the accumulated patterns of adaptive traits and behaviors brought about by natural selection are very ephemeral. They slowly sediment over many generations but they can be wiped out by a single large-scale bifurcation, like the onset of the ice age. So what then corresponds here to the process of cementing together loosely accumulated pebbles into hardened sedimentary rock? The answer, according to the discipline of macroevolutionary dynamics, is the process of "speciation," that is, the birth of a new species. When a portion of a population becomes reproductively isolated from its parent group, the information contained in its gene pool becomes permanently injected into the larger phylogenetic lineage to which both groups belong. Speciation acts like a ratchet, preventing accumulated adaptations from being eroded away. In this form, what was a loosely bonded set of anatomical and behavioral traits is now hardened into the more or less permanent structure of a particular species.[53]

our circadian rhythms are dynamical processes — they are guided by periodic attractors — they are capable of synchronizing or "entraining" to an external rhythm. Although entrainment to the light–dark cycle of the regular Earth day, for example, can by desynchronized (as in jet lag), the same dynamic flexibility that allows self-organizing clocks to adjust to the external environment also allows them to undergo other kinds of bifurcations. Thus, a flash of light at a critical moment (of bifurcation) can send one's clock into a totally different period or stop it altogether. A whole range of pathological phenomena has been associated with the occurrence of bifurcations and has received the name "dynamical diseases."[55]

The phenomenon of entrainment — the spontaneous phase synchronization of different oscillating entities — is common in nature. One well-known example is the slime mold amoeba: in normal circumstances, a group of these amoebas will behave as unrelated individuals, but when the level of environmental nutrients reaches a critically low value, they assemble themselves into a coherent colony with differentiated "organs." Entrainment also occurs in laser light, which differs from ordinary light in that the photons oscillate "in phase" (that it, they are synchronized), resulting in the emission of a coherent beam. Entrainment takes place in so many physical systems that it is, in a sense, a mechanism-independent process:

> Populations of crickets entrain each other to chirp coherently. Populations of fireflies come to coherence in flashing. Yeast cells display coherence in glycolytic oscillation. Populations of insects show coherence in their cycles of eclosion (emergence from the pupal to the adult form).... Populations of women living together may show phase entrainment of their ovulation cycles. Populations of secretory cells, such as the pituitary, pancreas, and other organs, release their hormones in coherent pulses.[56]

In phase space, entrainment appears as a torus-shaped attractor, which the trajectories of different systems (the oscillating entities) come to wrap around. The transition from nonsynchronized to synchronized oscillations can be understood as a bifurcation in which a set of separate limit cycles transform themselves into a single attractor. Entrainment is common in living systems because periodic attractors are their main form of organization. Indeed, one crucial difference between geological and organic strata is the former's tendency to develop around points of static equilibrium (minima of energy, point attractors), as opposed to the latter's tendency to make use of forms of dynamic equilibrium (periodic and even chaotic attractors). Were one to track the flow of matter around the planet, one would see how it becomes stratified along these lines. For example, although the key element of life, carbon, is for the most part locked in rocks, some of it — notably in the form of carbon dioxide — moves freely through the biosphere; some of this, in

Dielectric in the process of breakdown.

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Dielectric in the process of breakdown.

turn, is trapped cyclically by plants (through photosynthesis), captured in their biomass and released when their leaves fall in autumn.

There is a sense, then, in which we are all inhabited by processes of nonorganic life. We carry in our bodies a multiplicity of self-organizing processes of a definite physical and mathematical nature — a set of bifurcations and attractors that could be determined empirically, at least in principle. Yet, is there any way *to experience* this nonorganic life traversing us (for example, through the use of meditation techniques or psychedelic chemicals to "destratify" ourselves)?[57] As noted above, there *is* a "wisdom of the rocks" from which we can derive an ethics involving the notion that, ultimately, we too are flows of matter and energy (sunlight, oxygen, water, protein and so on). At any moment in these flows, we can distinguish some portions that are more viscous (hardened, stratified) than others. An ethics of everyday life, in these terms, would involve finding the relative viscosities of our flows, and giving some fluidity to hardened habits and making some fleeting ideas more viscous — in short, finding, through experimentation, the "right" consistency for our flows (the "right" mixture of rigid structures, supple structures and self-organizing processes).

Clearly, though, it is impossible to derive ethical lessons from the machinic phylum without considering processes of self-organization and stratification at the level of society. Animal and human societies, like individual organic bodies, are also "crossed" by the machinic phylum. For example, a particular population of animals is regulated by a simple equation concerning its birth and death rates and the reservoir of its environmental resources. This simple equation has been shown to undergo bifurcations: a population that for many years tended toward a steady-state equilibrium may suddenly begin to oscillate between two extremes. Similarly, the respective biomasses of two populations (one prey, the other predator) are also linked by equations susceptible to bifurcation.[58]

Phalanx of soldiers.

Elaborating on the observation that phase transitions and other bifurcations occur at the level of animal populations, Arthur Iberall has proposed a model of human society in terms that emphasize self-organizing processes. In his view, societies function as an ensemble of flows and the reservoirs driving those flows: water, metabolic energy, bonding pressures, action modes, population, trade, technology and so on. In doing so, Iberall is not out to replace standard accounts of human development but "to stress the role of flows and phase transitions in determining social field stability." He goes on to say:

> I view the discontinuous social change manifested by the appearance of food-producing societies (e.g., from hunting-gathering to horticulture to

> settled agriculture) as evidence of internal rearrangements, new associations and configurations, and a new phase condensation — as if a gaslike phase of matter were becoming liquidlike or solid state–like.... At his beginning, modern man apparently lived in hunting–gathering groups operating in a range appropriate to human size and metabolism.... If, as is appropriate to his size, man had the typical mammalian metabolism and roaming range of about 25 miles/day, cultures separated on the order of 50 miles would have little interaction.... The 70- to 100-mile separation of populations, as empirically found, is highly suggestive of a system of weak force, "gaslike" interactions.... [D]ecreases in the levels of the required potentials (temperature, water, food) cause condensation [liquification] of small bands on fixed centers of population.... The nature of the social phase condensation, however, depends on the amplifying capability of the technological potential. Associated with those two chief potentials — water supply and technology (tools) — came changes in modes of living, improvement in the use of water resources, and localized social development through the domestication of plants and animals....[59]

Eventually, these "fluidlike" social formations "crystallized" into stratified civilizations. Based on the archaeological record, Iberall concludes,

> civilizations began when there was extensive trade (convective flow) among population concentrations (condensations). The urban centers held cumulative populations greater than 2500 and were composite groups. The threshold size can be estimated from the absence of complex cultures of smaller population.[60]

This picture of social evolution corresponds in many ways to the creation scenario of our hypothetical crystal planet. Clearly though, if a simple liquid solution can harden into crystal or glass, ice or snowflake, depending on the multiplicity of nonlinearities shaping the solidification process, human societies — which have a wider range of attractor types — have far more leeway in how they develop stable configurations. And while there is much to be learned from analyzing in detail the actual processes of stratification and destratification that have occurred in different societies at different times, even a picture as simple as this already points to certain principles of a "geological ethics." Notably, society cannot be understood as climbing a ladder of "progress," as though hunter–gatherers, agriculturalists and "civilized" communities were stages on a path toward ever-increasing perfection. Rather, understanding these transformations as phase transitions would imply that a State apparatus is not essentially better than a "primitive" society, since after all, there is nothing intrinsically better about a solid than a liquid.

From the viewpoint of a geological ethics, early societies may even have achieved a better consistency among their flows, a viscosity more in tune with their ecosystems than our own. Indeed, it seems that some early societies may have sensed the approach of social solidification and

developed mechanisms to prevent actualizing such a bifurcation.[61] This, of course, is not to say that we should return to some lost paradise of a "savage state," a bygone era of greater innocence and harmony. Rather, we must work on the society in which we find ourselves, tracking the flows of matter and energy, destratifying hardened institutions, setting into flux human practices that have sedimented — in short, we must find the right viscosity for our fluxes, the exact consistency that would allow humanity to self-organize without the need for coercion and war.

Iberall pictures the flow of goods along trade routes as an example of convective flow, as though precapitalist markets were indeed self-organizing structures creating order out of chaos. We may have to discover in the history and present of human practices those institutions that realize best the workings of the machinic phylum, or, more precisely, the degrees of stratification of each of its components: those flowing more or less freely, those sedimented into more or less supple structures and those rigidified into permanent institutions (entrenched political hierarchies, inflexible belief systems). The geological strata teach us that even the seemingly most rigid structures can flow (however slowly), mutate (metamorphic rocks) or even be reincorporated into self-organizing processes (convection flows of lava).

Part of such an effort would involve creating "maps" showing the attractors that govern the dynamical behavior of social flows, and more important, the bifurcation regions where — to paraphrase Prigogine — a "dangerous idea" can amplify itself by taking advantage of the nonlinearities that guarantee the stability of a given social system. The work of Deleuze and Guattari is exemplary for the creation of such maps: they show how our lives may be viewed as a composite of rigid structures (family, school, military service, office, marriage), supple structures (temporary alliances, transitory love affairs, loosely knit groups) and, finally, "lines of flight," the bifurcations that could allow us to change our destinies as defined by those two types of structures.[62] In every area of human reality (art, politics, love), they attempt to "measure" the degrees of stratification of the flows of matter and energy at work in these domains. For example, after showing how music originates from the expressive powers of matter itself (in particular, the self-organizing processes of animal territories that give rise to bird songs), they argue that music has a greater capacity to "destratify" than does painting. It is as though the modulated flows of air that we experience as music have a greater capacity to set our emotions and thoughts into flux than do the more viscous, spatial flows of form and color found in painting.[63]

Marching formation at Nazi rally.

It follows, then, that the kind of "stratometers" that could perform these measurements of relative viscosity in various material and energy flows need not all be mathematically based. A great novel can, for a given society, capture the coexistence and interactions of rigid structures and

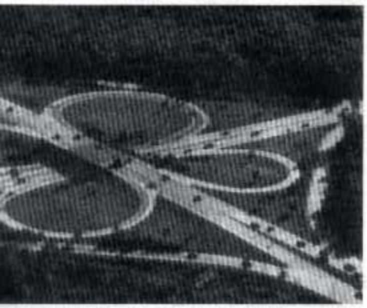
sedimented habits, as well as the active and creative forces driving a society to undergo bifurcations. That there is plenty of room for intuition and experimentation in tracking the machinic phylum in no way obviates the need for, or possibilities of, stratometers of a more mathematical kind. Some might be computer programs capable of creating complex phase portraits of interacting dynamical systems, and of detecting their various elements — those operating linearly in equilibrium conditions (rigid structures), those that are nonlinear in near equilibrium conditions (supple structures) and, finally, those operating nonlinearly far from equilibrium. (Only the latter allows the flows of matter and energy to express themselves.)

In order to visualize better the uses to which we could put these stratometers, consider as examples two kinds of human institution operating at different degrees of stratification: the marketplace and the State. As noted, cities and towns may be seen as composed of a series of reservoirs (water, protein, labor and so on) driving a variety of flows and, in the process, giving rise to the institutions that channel, amplify or control these flows. On the one hand, the more or less fluid structures of markets arise from the spontaneous interaction of many agents, without any central organ directing the process of assembly. On the other, the more rigid hierarchical structure of State institutions comes to life not spontaneously but through the goal-directed activities of an elite.

Mainstream economic science, however, fails to capture the fluid nature of market dynamics: the operation of markets is treated as though it resembled the growth of perfect crystalline structures, that is, as though it were governed by a tendency to move toward a single point of equilibrium (where supply meets demand) — a point of optimal efficiency, from the viewpoint of society as a whole (full employment equilibrium). In order to obtain this well-behaved dynamics from their models, though, economists must rely on two unwieldy assumptions: first, that there exists perfect competition among all economic agents (that is, no monopolies or oligopolies manipulating prices); and second, that these agents have perfect information about market conditions as well as an unbounded rationality to act on that information, so that each is able to negotiate the deals that maximize the agent's benefit (utility).[64] But when these unrealistic assumptions are relaxed, the dynamics of the market begin to resemble in many respects those of self-organizing structures in liquids, from the controlled flow of a convective cell to the wild patterns of turbulence or even solitons. If, alternatively, the relatively long-lasting and stable structures of some markets are understood as suggesting that a "solid" metaphor were appropriate, market behavior would resemble, among all solids, that of glass — which is guided by multiple equilibria — more than that of a crystal with a single equilibrium. The more amorphous structure of glass results precisely

Liquid crystals.

from the conflicting constraints imposed by many attractors (local energy minima) and from the possibility of being "trapped" by an attractor that prevents the optimal use of energy. Markets function like glass in that, in the presence of imperfect conditions (imperfect decision making), they can be trapped in suboptimal equilibria — like a supply–demand equilibrium with high unemployment — as has been well known since Keynes's work in the 1930s.[65]



Cloverleaf intersection.

As Joseph Schumpeter showed around the same time, moreover, the equilibrium on which a market settles need not be a stationary state: more likely than not it will be a cycle instead. The upswing of a cycle will bring prosperity, and the downswing a period of recession and high unemployment. This behavior has been accounted for by models that generate these nonlinear dynamics through a periodic attractor: Kondratieff cycles, for example, in which prices and interest rates follow a fifty-two-year long-wave motion — which has been operating for at least two centuries — have been explained as resulting from positive feedback loops forming in specific areas of the economy (specifically, in the capital goods sector, which produces the machinery needed to generate consumer goods). By amplifying small fluctuations in the relevant sector, these positive feedback loops drive the economy away from equilibrium and trigger a Hopf bifurcation, transforming a steady-state equilibrium into a stable oscillatory motion.[66]

Modeling markets as self-organizing structures has nothing to do with the famous "invisible hand" that, according to some economists, guides a market toward optimal levels of efficiency when left to its own devices. On the contrary, the presence of nonlinear effects throughout the economy — from multiplier–accelerator effects in investment and finance to the multiplicity of delays, bottlenecks, surpluses and shortages stemming from the limited rationality of economic agents — means that real markets must be able to cope with life far from equilibrium, and indeed, to create special buffering structures (inventories, retail stores, banks) for this purpose.[67] In short, to the extent that markets emerge and operate spontaneously, they are incapable of achieving optimal equilibria on their own. Other kinds of human organizations, on the other hand — the State, sedentary armies, large corporations — are more capable of goal-directed optimization; these latter can be treated as crystallizations in the flows of matter and energy.

And yet, not even these are perfect crystalline structures, for just as the dynamics permitting actual formation of crystals is complicated by the Earth's real conditions — by gravity, notably — so are the dynamics of human institutions. If one wants to grow "pure" crystals, one must do so (for now) aboard a space shuttle, where the single point of equilibrium guiding their formation is artificially isolated from other influences. Should one attempt to do so on Earth, crystals require special

complex computers, the sum of the decision-making abilities of many micro-economic agents (consumers and producers). Mainstream economics regards these agents as perfectly rational, so the computational abilities of the economy as a whole are seen simply as a reflection of this underlying rationality. But if nonlinear economics is right, if agents are essentially limited in their rationality as well as in their access to information, then the economy as a whole may have to acquire its power of computation dynamically, that is, by operating poised at the edge of chaos.

Because the problems raised by hybrid systems involve both dealing with flows of matter and energy and studying the stratifications that form in those flows, we might do well to learn from the experiences of those who were the first to track the machinic phylum — artisans and metallurgists. Before the advent of modern methods, they did this by using their instincts and the empirical know-how accumulated through the ages. They had to track everything from stratified ore deposits to a metal's melting and crystallization points, and then to experiment with different ways of crossing those bifurcations through forging techniques; they had to look for their own hybrids, that is, synergistic combinations of metals in which the whole spontaneously becomes more than the sum of its parts (alloys), and to allow the materials to have their own say in the final form produced. All of this involved following a given material's local accidents and imperfections, rather than imposing a rigid, preplanned form on it.

According to metallurgist Cyril Stanley Smith, this know-how had been developed well before the Greeks began to apply formal reasoning to these problems, and it was therefore mostly of a sensual nature.[75] These artisans, in a sense, developed a special ability to follow the phylum, to track the machinic effects created by nonlinear phenomena in nature, and it is this ability that we must acquire again if we are to help social hybrid structures evolve. (As *sensual* knowledge, this know-how would constitute yet another stratometer, one built into our own bodies.)

Artisans and metallurgists, though, are not the only source of insight for such a project: the Earth itself has been dealing with flows of matter and energy for millennia, and herein lies the wisdom of the rocks from which we might derive our inspiration. In geological, hydrological and organic strata (as well as in the two other strata that bind us, intentionality and language[76]), we can always find some elementary components that are not only less stratified, less bound to their attractor, but that are also capable of destratifying their own and other systems' components by pushing them away from their attractors, toward the border of their basin of attraction, where small fluctuations can then tip the system into a completely new regime. In the lithosphere, for example, this role is played by metallic catalysts: by interacting with various other elements and thereby allowing them to transform each other chemically,

Polyhedral salt crystals.

they enable inert matter to explore the space of possible chemical combinations, in a nonconscious search for new machinelike solutions to problems of matter and energy flow. It is as though catalysts were, to use Deleuze and Guattari's term, the Earth's own "probe heads," its own built-in device for exploration; and indeed, to the extent that autocatalytic loops and hypercycles were part of the machinery involved in the "discovery" of life, these probe heads allowed physicochemical strata to transform themselves and their milieus into completely new worlds.

We ourselves must become this kind of probe head in our own strata, and allow society to explore and experiment with the possible machinic solutions to its own problems. We must create stratometers of every kind — mathematical *and* nonmathematical — and get to work mapping the attractors that define our local destinies and the bifurcations that could allow us to modify these destinies. And though this is undoubtedly an enterprise fraught with dangers, we can derive some comfort from the hints of the machinic phylum that have recently become visible to us and seem to indicate there may be ways of evading our currently doomed environmental destiny.

NOTES

1. Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1970), p. 116.

2. Ian Stewart, *Does God Play Dice? The Mathematics of Chaos* (Oxford: Basil Blackwell, 1989), p. 186.

3. Hans Degn, Lars Olsen and John Perram, "Bistability, Oscillation and Chaos in an Enzyme Reaction," in Okan Gurel and Otto Rossler, eds., *Bifurcation Theory and Applications in Scientific Disciplines* (New York: New York Academy of Sciences, 1979), p. 623.

4. Ilya Prigogine and Isabelle Stengers, *Order out of Chaos* (New York: Bantam, 1984), p. 14.

5. See, for example, Philip W. Anderson and Daniel L. Stein, "Broken Symmetry, Emergent Properties, Dissipative Structures, Life: Are They Related?" in Eugene Yates, ed., *Self-Organizing Systems* (New York: Plenum, 1987), p. 454.

6. Peter Decker, "Spatial, Chiral and Temporal Self-Organization through Bifurcation in 'Bioids': Open Systems Capable of Generalized Darwinian Evolution," in Gurel and Rossler, eds., *Bifurcation Theory*, p. 236.

7. Gregoire Nicolis and Ilya Prigogine, *Exploring Complexity* (New York: Freeman, 1989), p. 187.

8. David Campbell, "Nonlinear Science: From Paradigms to Practicalities," in Necia Grant Cooper, ed., *From Cardinals to Chaos* (Cambridge, Eng.: Cambridge University Press, 1989), p. 225.

9. John Briggs and F. David Peat, *Turbulent Mirror* (New York: Harper and Row, 1989), p. 121.

10. Ibid., p. 123.

11. Prigogine and Stengers, *Order out of Chaos*, p. 155.

12. Ary L. Goldberger, David R. Rigney and Bruce J. West, "Chaos and Fractals in Human Physiology," *Scientific American* 262.2 (Feb. 1990), p. 42.

13. Alwyn C. Scott, "Solitons in Biological Molecules," in David Pines, ed., *Emerging Syntheses in Science*, Santa Fe Institute Studies in the Sciences of Complexity (Reading, Mass.: Addison-Wesley, 1988).

14. Briggs and Peat, *Turbulent Mirror*, p. 123.

15. Alwyn C. Scott, "Introduction," in Peter Christiansen and R. D. Parmentiert, eds., *Structure, Coherence and Chaos in Dynamical Systems* (Manchester, Eng.: Manchester University Press, 1989), p. 2.

16. David Campbell, "Introduction to Nonlinear Dynamics," in Daniel Stein, ed., *Lectures in the Sciences of Complexity*, Santa Fe Institute Studies in the Sciences of Complexity (Reading, Mass.: Addison-Wesley, 1989), p. 90.

17. Stewart, *Does God Play Dice?*, p. 83.

18. Hermann Haken, "Synergetics and Bifurcation Theory," in Gurel and Rossler, eds., *Bifurcation Theory*, p. 365.

19. Scott, "Introduction," in Christiansen and Parmentiert, eds., *Structure, Coherence and Chaos*, p. 1.

20. "We always get back to this definition: the machinic phylum is materiality, natural or artificial, and both simultaneously; it is matter in movement, in flux, in variation, matter as conveyor of singularities and traits of expression" (Gilles Deleuze and Félix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*, trans. Brian Massumi [Minneapolis: University of Minnesota Press, 1987], p. 409). Here, the term "singularities" refers to phase transitions and other bifurcations; "traits of expression" are the "emergent properties" that arise in material systems when their global behavior is guided by attractors; and "emergent properties" are those synergistic properties that distinguish a whole as being more than the sum of its parts (properties that cannot be deduced from the components' properties, but only from their interactions).

21. Many may well have "seen" nonorganic life long before the advent of computers: Deleuze, for example, credits several philosophers (from the ancient Stoics to Spinoza, Nietzsche and Bergson) with having "tracked" the machinic phylum in various ways.

Ralph Abraham divides the historical study of bifurcations into three periods, according to the instrument of study used: "The period of direct observation may be much older than we think, but let us say that it begins with the musician Chladni, contemporary of Beethoven, who observed bifurcations of thin plate vibrations.... Analogous phenomena discovered in fluids by Faraday are still actively studied. These experiments, so valuable because the medium is real, suffer from inflexibility — especially in choosing initial conditions.... The next wave of bifurcation experiments, which I shall call the analog period, begins with the triode oscillator. The pioneering work of van der Pol (in the 1920's)... produced a flexible analog computer, and institutionalized the subharmonic bifurcations.... The development of the early computing machines ushered in the digital period. Well-known numerical

methods were implemented from the start, and graphical output began to appear in the literature. The pioneering papers of Lorenz, and Stein and Ulam, are still studied" ("Dynasim: Exploratory Research in Bifurcations Using Interactive Computer Graphics," in Gurel and Rossler, eds., *Bifurcation Theory*, p. 676).

22. Useful introductions to phase space can be found in: Stewart, *Does God Play Dice?*, ch. 5; James Gleick, *Chaos: Making a New Science* (New York: Viking, 1987), pp. 49–52; and Ralph Abraham and Christopher Shaw, *Dynamics: The Geometry of Behavior*, The Visual Mathematics Library (Santa Cruz, Cal.: Aerial Press, 1985), vol. 1.

23. Prigogine and Stengers, *Order out of Chaos*, p. 206.

24. See Campbell, "Introduction to Nonlinear Dynamics," in Stein, ed., *Lectures in the Sciences of Complexity*, p. 26.

25. A more detailed account of phase transitions from plasma to crystal can be found in Hans Gutbrod and Horst Stocker, "The Nuclear Equation of the State," *Scientific American* 265.5 (Nov. 1991), p. 61.

26. Although the transition from plasma to gas is not in fact "sharp" in the same way that those from gas to liquid or from liquid to solid are, this does not substantially affect this example.

27. According to quantum physics, the virtual orbits around naked nuclei are not attractors but minima of free energy — that is, the equations of quantum physics are linear, and hence do not give rise to self-organization as nonlinear equations do. Many of the pioneers of quantum physics, though — Enrico Fermi, Werner Heisenberg, Louis de Broglie, John von Neumann — envisioned a future in which their discipline would become nonlinear. Various methods have since been proposed that would permit elementary particles to be described in terms of attractors. In *Toward a General Science of Viable Systems* (New York: McGraw Hill, 1972), p. 33, Arthur Iberall offers a nonlinear theory of matter and energy (ranging from atoms to human societies) relying exclusively on limit cycle attractors (which tends to make it mechanistic at points). Iberall challenges received quantum theory, arguing that it provides only a "statistical algorithm" that undoubtedly gives the right results but no conceptual structure with which to understand them (an ad hoc "numerology"); he proposes that it be replaced with a theory that characterizes the eigenvalues (fundamental parameters) of a field in terms of nonlinear limit cycles.

28. Richard Palmer, "Broken Ergodicity," in Stein, ed., *Lectures in the Sciences of Complexity*, p. 275.

29. "The clothes you wear, be they wool, cotton, or silk, are animal or plant gels. They are dyed with colors, which in many instances... are colloid in type.... The leather in your shoes is an animal gel, closely related to the prototype of the colloids, gelatin.... The wood of the chairs in which you rest is made of cellulose, which in all its various forms is colloid in nature.... [They] are held together by glue or by steel nails and steel is a colloid solid solution.... The paper upon which you write...[and] the ink in your fountain pens [are] probably also colloid.... [C]olloid, too, is the hard rubber of your pen holders, prepared from that notoriously colloid mother substance, soft rubber" (Wolfgang Ostwald quoted in Milton

Populations," in *Dynamical Chaos* (London: Royal Society, 1987); and Manfred Peshel and Werner Mende, *The Predator–Prey Model: Do We Live in a Volterra World?* (Vienna: Springer, 1986).

59. Arthur Iberall, "A Physics for the Study of Civilizations," in Yates, ed., *Self-Organizing Systems*, pp. 531–33.

60. Ibid., p. 533.

61. See Pierre Clastres, *Society against the State*, trans. Robert Hurley (New York: Zone Books, 1987), p. 189ff. "Societies against the State" have also been termed "anticivilizations" to stress their effective resistance to crystallization into a stratified society: see Gordon W. Hewes, "Agriculture and Civilization," in Matthew Melko and Leighton R. Scott, eds., *The Boundaries of Civilization in Space and Time* (Landham, Md.: University Press of America, 1987), p. 199.

62. See, for example, Gilles Deleuze, "Politics," *Semiotext(e)* 8 (1978), pp. 154–63.

63. Deleuze and Guattari, *A Thousand Plateaus*, ch. 11: "The Refrain."

64. In some mathematical models, periodic and even strange attractors can result if we maintain these two assumptions: in other words, even if the model allows markets to clear perfectly (supply always exactly satisfying demand), and the agents are given perfect foresight, cycles and chaos can result if we include nonlinear financial constraints (for example, limited access to borrowing). See Michael Woodford, "Finance, Instability and Cycles," in Willi Semmler, ed., *Financial Dynamics and Business Cycles: New Perspectives* (Armonk, N.Y.: M. E. Sharpe, 1989).

65. On the phenomenon of "locking in" suboptimal equilibria, see W. Brian Arthur, "Self-Reinforcing Mechanisms in Economics," in Philip W. Anderson, Kenneth J. Arrow and David Pines, eds., *The Economy as an Evolving Complex System* (Reading, Mass.: Addison-Wesley, 1988).

66. A recent nonlinear model of Kondratieff cycles can be found in: J. D. Sterman, "Nonlinear Dynamics in the World Economy: The Long Wave," in Christiansen and Parmentiert, eds., *Structure, Coherence and Chaos*. Also of note is the pioneering work of Richard Goodwin, who has been using nonlinear models since the 1950s: see his *Essays in Nonlinear Economic Dynamics* (Frankfurt: Peter Lang, 1989). There are many models of Kondratieff cycles, both linear and nonlinear; for a survey, see Christopher Freeman, ed., *Long Waves in the World Economy* (Stoneham, Mass.: Butterworth, 1983).

67. Richard H. Day, "Adaptive Economics," in Robert Crosby, ed., *Cities and Regions as Non-Linear Decision Systems* (Washington, D.C.: AAAS, 1983), p. 10.

68. On the role of dislocation structures in real crystals, see Allan Bennet, "The Importance of Imperfections," in Sharon Banigan, ed., *Crystals, Perfect and Imperfect* (New York: Walker, 1965), p. 85. On human elites as dislocations, see Iberall, *Toward a General Science*, p. 208.

69. Robert Crosby, "Asking Better Questions," in Crosby, ed., *Cities and Regions*, p. 10.

70. Ibid., p. 12.

71. Ibid., p. 21.

72. C. S. Holling, "Resilience and Stability in Ecosystems," in Erich Jantsch and Conrad H. Waddington, eds., *Evolution and Consciousness* (Reading, Mass.: Addison-Wesley, 1976), p. 87.

73. Stuart A. Kauffman, "Antichaos and Adaptation," *Scientific American* 265.2 (Aug. 1991), p. 82; and Christopher Langton, "Life at the Edge of Chaos," in Langton, Charles Taylor, J. Doyne Farmer and Steen Rasmussen, eds., *Artificial Life* (Reading, Mass.: Addison-Wesley, 1992), p. 85.

74. Langton, "Life at the Edge," p. 82. If as Langton and Kauffman think, poised systems are where complexity and variety peak (i.e., are "crossed" in the most intense form by the machinic phylum), then we may imagine a different set of policies (or even philosophies of everyday life). We would have to track these special zones, for example, by destratifying ourselves (that is, by pushing our "solid" components a little, but only a little, toward the "liquid" state). Just exactly how much to "liquify" should be established through careful experimentation, since there are dangers if one goes too far (one may be swallowed up by a chaotic attractor). This is how Deleuze and Guattari put it: "You don't reach the [machinic phylum] by wildly destratifying.... If you free it with too violent an action, if you blow apart the strata without taking precautions, then instead of [tapping into the phylum] you will be killed, plunged into a black hole, or even dragged toward catastrophe. Staying stratified — organized, signified, subjected — is not the worst that can happen; the worst that can happen is if you throw the strata into demented or suicidal collapse, which brings them back down on us heavier than ever. This is how it should be done: Lodge yourself on a stratum, experiment with opportunities it offers, find an advantageous place on it, find potential movements of deterritorialization, possible lines of flight, experience them, produce flow conjunctions here and there, try out continuums of intensities segment by segment, have a small plot of new land at all times" (*A Thousand Plateaus*, pp. 160–61).

75. Cyril Stanley Smith, *A Search for Structure* (Cambridge, Mass.: MIT Press, 1982), p. 113.

76. Intentional strata correspond to the world of beliefs and desires as they exist in the animal kingdom, past a certain level of complexity of informational flow. The sedimentations and hardenings that make up these strata grow "on top" of the organic stratum (they use the brain as their substratum). They, in turn, provide the raw materials for the emergence in humans of linguistic strata. Deleuze and Guattari offer theories on these two strata, which they call "subjectification" and "signifiance." I shall produce a more detailed exposition of these topics in my forthcoming book *Chaos and the Millennium*.