

A GLOSSARY OF TERMS AND CONCEPTS ASSOCIATED WITH NON-EQUILIBRIUM THERMODYNAMIC SYSTEMS

(Dissipative Structures, Artificial Life, Chaos, and Complexity)

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Most of the interesting things in this universe are not linear, or predictable. They are nonlinear and unpredictable, but produce the vast majority of the great complexity and order that we observe all around us. The theories of dissipative structures, stratified stabilities, chaos and complexity deal with the origins of these phenomena.

Many of the phenomena associated with these theories are not intuitively obvious, in fact they are often counter intuitive. Much of our inability to understand or even recognize them in the past was because of our inability to model or explore them effectively. Modeling these theories often requires daunting calculations, virtually impossible before computers. But even with computers, the concepts are often still puzzling, and elusive. It may seem at first that some of the concepts defined or described below are unrelated, but in fact they are all just different facets of the same phenomenon. Part of the confusion is historical, since each of these theories was developed independently by individuals with different backgrounds and interests. Some of this diversity is expressed in the multiple definitions below for some of the terms, but these are definitions/descriptions used by the originators of these theories.

ALGORITHM - an expeditious formula. A computational procedure designed to produce a particular outcome. For example, $X_{\text{next}} = rX(1-X)$.

ATTENUATION - to diminish to extinction (zero) or to stabilize at some value. The tendency for a system to diminish its oscillations.

AUTOPOIESIS - *auto* = self; *poiesis* = making. Term coined by Maturana and Varela to refer to the distinctive circular organization of living systems.

- % "Living systems . . . [are] organized in a closed causal circular process that allows for evolutionary change in a way the circularity is maintained, but not for the loss of circularity itself." (Capra)
- % The key characteristic of a living network is that it continually produces itself Thus, "being and doing of [living systems] are inseparable, and this is their specific mode of organization."
- % Autopoiesis is a net work pattern in which the function of each component is to participate in the production or transformations of other components in the network. In this way, the network continually makes itself. It is produced by its components and in turn produces those components." (Capra, p 162)

% The properties of autopoietic network include (ala Fleishaker):

- < SELF-BOUNDED - means that the system's extension is determined by a boundary that is an integral part of the network.
- < SELF-GENERATING - means that all components, including those of the boundary, are produced by processes within the network.
- < SELF-PERPETUATING - means the production processes continue over time, so that all components are continually replaced by the system's processes of transformation.

According to Maturana and Varela the concept of autopoiesis is necessary and sufficient to characterize the organization of living systems. However, this characterization does not include any information about the physical constitution of the systems components. (Capra, p 99)

Autopoiesis is a general pattern of organization, common to all living systems, what ever the nature of the components.

To find out whether a particular system is alive, all we need to do is find out whether its pattern of organization is that of an autopoietic network.

(COMPLEX) ADAPTIVE SYSTEMS (CAS) (OR CA AGENTS) - any complex system which is capable of exchanging information with its environment, and changing and evolving to adapt to that environment. A CAS can be any open system, including organisms, computer programs and economic systems, as long as they exhibit the properties of open, complex systems.

ADAPTIVE LANDSCAPE -

1. A "world" in which adaptive agents interact with world (environmental) variables or other adaptive agents in a search for optimal conditions (fitness).
2. An "environment" in which all possible variations in environmental parameters can be laid out and specified, and across which Adaptive Systems can evolve.

The adaptive landscape can be something real, like the Amazon rain forest, or an attractor in phase space, or an electronic ecosystem in a computer, or a chemical phase diagram. They often are created and exist as mathematical models on which all possible variations in adaptive fitness (potential evolutionary success) are depicted by peak heights on an imaginary landscape.

The adaptive agent can be a real organism, a genetic algorithm, a computer program (like a computer virus), or a chemical system seeking equilibrium.

APERIODIC BEHAVIOR - Occurs when no variable describing the state of a system undergoes a regular repetition of values (Kellert, p 4)

ARTIFICIAL LIFE (ALIFE) -

1. - A branch of research that works to discover basic principles of life by creating computer-based "life" on which experiments can be easily conducted.
2. - Devoted to the creation and study of lifelike organisms, and systems built by humans. The stuff of this life is nonorganic matter, and its essence is information. (Levy, 1992)
3. - The study of artificially created systems that embody at least some behaviors characteristic of "real" life. (Prata, 1993)
4. - Based on the following premises.
 - A The essence of life is process, not the physical structure
 - B Since the process is the essence, the medium in which the process occurs is merely a matter of convenience

C The self-organizing aspect of life is a consequence of a natural law or laws and should operate in any system of comparable complexity.

ATTRACTOR -

1. - A region of phase space that "attracts" all nearby points, as time passes, or a 'region of phase space' which exerts a 'magnetic' appeal for a system, seemingly pulling the system toward it." (Briggs and Peat, p 36).
2. - By analogy, imagine a hilly landscape surrounding a valley. A ball placed anywhere in the landscape will roll down the hills toward the valley. It doesn't matter where the ball starts or how fast it is rolling, it eventually ends up at the bottom of the valley - the attractor.
3. - We can generalize an attractor as any state toward which a system naturally evolves. For example, biological fitness is an attractor toward which species evolve.
4. - Types of attractors

FIXED POINT - a steady state system. The attractor is a single point, all trajectories spiral inward toward it, e.g. a pendulum steadily losing energy to friction until there is no motion at all and the pendulum hangs vertically, held fixed by the single point which is the center of gravity.

LIMIT CYCLE (or PERIODIC) - a system which repeats itself, exactly, continuously.

STRANGE (CHAOTIC) - An attractor that has been fragmented across phase space (Briggs and Peat, p 45). Turbulence is an example with multiple swirling eddies that never repeat exactly, and which may periodically change their direction of rotation. Many different strange attractors exist, include the Lorenz, Julian, and Henon. Each exists or is created by the working out of a particular chaos equation or set of chaos equations.



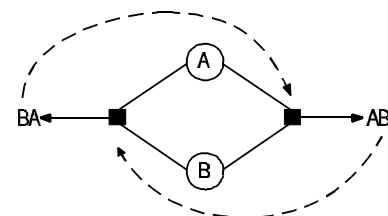
% "Strange attractors are fractal patterns made by a dynamical system exhibiting chaos." (Briggs, p 126)

% "One of the really strange things about strange attractors is that they do have a predictable overall form, but it's a form made of unpredictable details." (Briggs, p 139)

AVALANCHE - the behavior of a system poised at a critical state where minor disturbances lead to the precipitation of events (avalanches) which in size and timing follow a power law distribution (small events are common or frequent, large events are rare or infrequent).

"At some point there would be enough energy stored . . . that there would be a large chain reaction, where one (event) would trigger the next (event) by a domino effect. This process is called an avalanche. The avalanches would become bigger and bigger. Eventually, after thousands of events they would grow no further. As the simulation continued, there would be a stream of avalanches, some small, some intermediate, and a few big ones." (Bak, 1996, p 46)

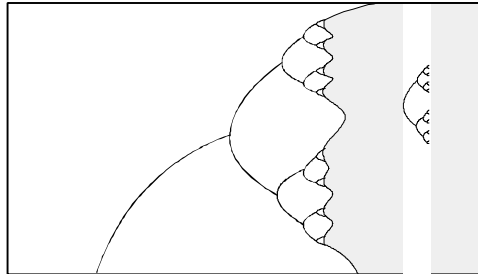
AUTOCATALYTIC NETWORK - An autocatalytic network is one where a series of components interact in a self-sustaining way, typically with no outside intervention. A simple autocatalytic set is to the right. Two dimer molecules, AB and BA, are formed from two simple monomers, A and B. Since AB and BA



catalyze the very reactions that join As to Bs to make the dimers, the network is autocatalytic, given a supply of "food" molecules (As and Bs) it will sustain itself.

BIFURCATION (period doubling) - The transition of a dynamical system from a stable steady state to one in which there are two equilibrium points, each of which is stable, and between which the system fluctuates back and forth.

Further bifurcations split the system to 4, then 8, then 16, then 32 . . . equilibrium points, leading eventually to no equilibrium points, i.e. aperiodic behavior or chaos (sensu stricto). Each split is a bifurcation. Because each split doubles the number of equilibrium points the process is also known as period doubling. Each period doubling or bifurcation means that the pattern of repetition, and the stability of the system, is breaking down. (Gleick, p 72)



% "A chaotic system constantly mixes things up, creating new directions in which the system can go. These moments of possibility are called bifurcation points. . ." (Briggs, p 112)

% "A bifurcation point is a threshold of stability at which the dissipative structure may either break down or break through to one of several new states of order." (Capra, p 191)

BUTTERFLY EFFECT - (see Sensitive Dependence on Initial Conditions)

1. - "Systems that display sensitive dependence on initial conditions exhibit what (Edward) Lorenz labeled the 'butterfly effect.' If we stipulate that the earth's weather is a chaotic system, then the flap of a butterfly's wings in Brazil today may make the difference between calm weather and a tornado in Texas next month." (Kellert, p 12)
2. - For want of a nail the shoe was lost.
For want of a shoe the horse was lost.
For want of a horse the rider was lost.
For want of a rider the message was lost.
For want of the message, the battle was lost.
For want of the battle, the war was lost.

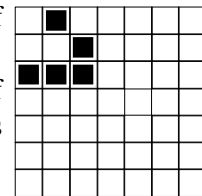
CHAOS (theory) - Chaos (Standard College Dictionary) - utter disorder and confusion. The dictionary chaos is not the kind of chaos discussed here. Chaos theory does not have a simple, single definition. Each of the following has been used to describe or get at the essence of chaos.

1. The quantitative study of unstable aperiodic behavior in determinist nonlinear dynamical systems. (Kellert, p 5)
2. $X_{next} = r X (1-X)$ A logistic equation which transforms from stability to chaos with increasing values of r.
3. A system which looks deterministic, but which because of the presence of nonlinear factors, turns out to be completely unpredictable. Despite the unpredictability, over the long term, distinct patters emerge (the strange attractors.)
4. "The phenomena exhibited by some nonlinear systems in which interdependencies in the system (feedback) cause very small errors in the initial measurements (or in the precision of ongoing

calculations) to be amplified to the point where the eventual result is unpredictable and widely varying." (Roetzheim, p 34)

5. A deterministic system which produces non-deterministic outcomes.
6. "A system in which a few things interacting produce tremendously divergent behavior; deterministic chaos; it looks random but its not." (Chris Langton, in Lewin, p 12)
7. A system with orderly disorder (Kellert, p 7).
8. "Apparent random recurrent behavior in a simple deterministic (clockwork-like) system" (H. Bruce Stewart, in Gleick).
9. "The irregular, unpredictable behavior of deterministic, nonlinear dynamical systems" (Roderick V. Henson, in Gleick, 1987).

CELLULAR AUTOMATA - An artificial life research tool consisting of a grid of cells (like a checkerboard), with each cell capable of assuming a state (e.g. alive=shaded and dead=unshaded), and a set of rules which determine the fate of each cell in succeeding generations (sample rule, "If a cell is dead and two of its neighbors are alive it will come alive the next generation").



CLOSED SYSTEMS - are those in which there is no internal transformation of energy. They are thermodynamically closed.

CONVERGENCE - said of an iterated system in which a sequence of oscillating values converge to a smaller and smaller difference, or finally to a single value.

COMPLEXITY (theory) - There are two uses of the term of complexity, one common, and one specific. The common one refers to a system in which the behavior is disordered and erratic. The only way to understand such a system is to describe the properties and behavior of every individual component. It is complex in a way that cannot be simplified. That is **not** the complexity referred to in complexity theory.

1. That region where the behavior of a system is fluid, dynamic, and able to change easily to new arrangements, patterns, and organizations, but not so fluid that no quazistable patterns can emerge.
2. A system in which complex causes produce simple effects (Cohen and Stewart).
3. A type of dynamical system intermediate between chaotic and fixed (periodic) behavior (Lewin, p 48).
4. A system in which the individual components, operating independently, produce order.
5. The narrow transition region between order and chaos. (Norman Packard, in Lewin, p 53).
6. The edge of chaos (Lewin, p 44).
7. A system poised at SOC (self organized criticality.)

COMPLEX ADAPTIVE SYSTEMS (CAS) (or CA Agents) - see Adaptive Systems

COMPUTATIONAL VIEWPOINT - The computational viewpoint in mathematics is the notion that to know a mathematical truth you must be able to compute it. That is, the outcome of an algorithm can only be known by calculating the algorithm.

The computational viewpoint of the Universe is that the material world and the dynamic systems in it are computers. The brain, the weather, the solar system, even quantum particles are all computers. They don't look like computers, of course, but what they are computing are the consequences of the laws of nature. According to computational viewpoint, the laws of nature are algorithms that control the development of the system in time, just like real programs do for computers. For example, the planets, in moving around the sun, are doing analogue computations of the laws of Newton.

DETERMINISTIC (system) -

1. - One in which the outcome is totally predictable from the initial conditions.
2. - A system which follows rigid laws. Before chaos theory included the idea that the future is completely predictable by following out from present conditions.

DISSIPATIVE STRUCTURES -

1. - "The system is dissipative, meaning that friction causes a loss of available energy: the system would wind down to motionlessness if the external source of energy . . . were removed." (Kellert, p 13)
2. - An open system that maintains its form or structure by a continuous dissipation (consumption) of energy (and information). (Ferguson, p 164)
3. - The theory for which Ilya Prigogine won the 1977 Nobel prize.
4. - A self organizing system.
5. - Properties
 - A. Highly organized but always in process.
 - B. The more complex a dissipative structure the more energy/information is needed to maintain it - that is, it is "far from equilibrium."
 - C. System is always in flux.
 - D. The more coherent or intricately connected the structure, the more unstable it is.
 - F. The more complex and coherent the system is the more unstable it is, and the more easily it can transform into a new, even more complex form.

ENTROPY -

1. "The name of the quality of a system that increases under the Second Law (of Thermodynamics) - mixing, disorder, randomness." (Gleick, p 257)
2. A measure of the amount of energy available to do work - the less energy available, the higher the entropy.
3. A measure of the disorder in a system - the more disorder, the higher the entropy.
4. A measure of the flow of information in a system. The more flow the lower the entropy, the less flow the higher the entropy.

EMERGENT (property) -

1. The whole is more than the sum of the parts.
2. An outcome which is the result of all the individual components interacting but which cannot be found in any one of those components.
3. A complex outcome emerging from the action of simple rules; local rules, global behavior.
4. Regularities of behavior that seem to transcend their own ingredients (Cohen and Stuart, p 232)

FITNESS LANDSCAPE - See Adaptive Landscape

FRACTAL (geometry) -

1. A type of geometry in which dimensions are not whole numbers (such as 0 for a point, 1 for a line, 2 for a square, and 3 for a cube).

One of the many peculiarities of fractal geometry is that an enclosed fractal geometric figure has a perimeter of infinite length, while the area is finite. Another feature is self similarity, that is, a fractal geometric figure enlarged to any scale always looks the same in its details with the same degree of complexity.

2. "A geometry that focuses on broken, wrinkled, and uneven shapes." (Briggs, p 158)
3. "Fractals are images of the way things fold and unfold, feeding back into each other and themselves." (Briggs, p 23)
4. "In general fractals are characterized by infinite detail, infinite length, no slope or derivative, fractional dimension, self similarity, and they can be generated by iteration." (Briggs and Peat, p 95)
5. One example of dimensions between whole numbers is a piece of paper crumpled into a ball. A sheet of paper is a Euclidian 2 dimensional object, but a ball is a 3 dimensional object. But a ball of crumpled paper is not fully three dimensional because it is composed of a 2 dimensional piece of paper. The ball of crumpled paper lies between dimension 2 and dimension 3.
6. A second example of dimensions between whole numbers begins with a string, which has 1 Euclidian dimension (it is equivalent to a line). But wrap the string into a ball, and the ball is three dimensional, except that it is composed of a one dimensional object, so its dimension must be between 1 and 3, but can't be 2. But from a long distance a ball of string can seem like a point, a 0 dimensional object. Thus, the dimension an object has may be strongly dependent on the perspective. Even a string, close up, is 3 dimensional. Only from a distance, or in the abstract, is it 2 dimensional.
7. A geometric figure for which no tangent lines exist.

Virtually every process and object in the universe follow the rules of fractal geometry and not the better known Euclidian geometry. One of the many powers of fractal geometry is that it is especially useful in describing chaos phenomena. There are three classes of fractals.

I LINEAR - fractals made of straight line segments which are iterated (repeated) ad infinitum

I NONLINEAR - fractals made up of curved line segments, but iterated ad infinitum. The Mandelbrot set is an example.

D RANDOM - fractals in which a random component is deliberately added into the iteration process. These are used to produce representations of landscapes and natural objects.

Many fractal processes are also chaos/symmetry hybrids. It is nature's common strategy to create form. A snowflake is a common example. The hexagonal structure of the single ice molecule directs the six-fold geometry of the snow flake, but the way the individual water molecules are added to the snowflake is a chaos/fractal process.

GENETIC ALGORITHM - a computer program which creates A-Life organisms with electronic genetic information and allows these organisms to exist, interact, and evolve in a computer based ecosystem.

ITERATE (Iteration) - to repeat. To do over and over.

LINEAR - said of a system in which there is a constant correspondence between one variable and another. Draws as a straight line on a graph.

LOCAL RULES/GLOBAL BEHAVIOR - the principle that the large scale patterns we see in a system are not the result of some overall design, but emerge from the working out of individual behaviors whose influence and effect is local and does not extend beyond its immediate surroundings..

NEGATIVE FEEDBACK (loop) - when the output of a system, fed back into the system, tends to dampen, or regulate the effect.

NON-EQUILIBRIUM THERMODYNAMICS - a term expressing the changed understanding of the implications of the 2nd Law of thermodynamics (which says entropy always increases) brought about by the theory of dissipative structures.

The 2nd law states that everything in the universe is heading toward maximum entropy, or the uniform distribution of heat. The implication is the universe is running down and only disorder and chaos (in the traditional sense) can result, the so-called "heat death" of the universe when all the stellar fires burn out as the universe settles into absolute blackness at absolute zero.

In the last century the paradox of life seeming to defy the second law by becoming more complex with time rather than running down, led to a lot of the controversy over Darwin's theory of evolution. Because of the 2nd law, many argued that the only way to explain the complexity of life was through arguments from design - that is a creator. The principles of non-equilibrium thermodynamic theories (including dissipative structures, stratified stability, chaos and complexity) demonstrate that such explanations are not essential since the earth is an open system, receiving continuous inputs of energy from the sun, and open systems (dissipative structures) are inherently self-evolutionary.

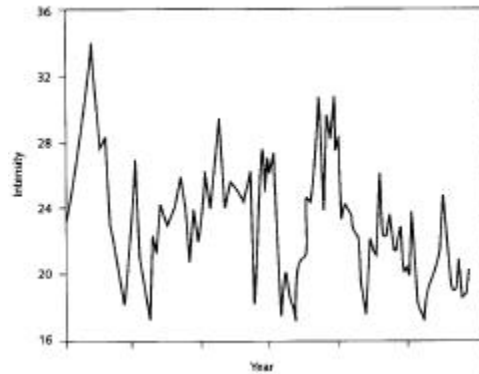
NONLINEAR - said of a system where one variable varies irregularly with respect to another variable. Nonlinear systems generally cannot be solved. "Nonlinear solutions tend to be stubbornly individual and peculiar. Unlike the smooth curves made by students plotting linear equations...plots of nonlinear equations show breaks, loops, recursions - all kinds of turbulence." (Briggs and Peat, p 24)

% "Equations that undergo sudden unpredictable behavior when iterated are nonlinear. Nonlinear equations are extremely sensitive in some regions of values, and those values mark the borderland between mathematical order and chaos." (Briggs, p 148)

% "For example, in a system of two variables x and y , expressions such as x^2 or $\sin(x)$ or $5xy$ would be nonlinear terms. These terms may stem from the inclusion of such factors as frictional forces or limits to biological populations." (Kellert, p 3)

% "In a nonlinear equation a small change in one variable can have a disproportional, even catastrophic impact on other variables. One difference between linear and nonlinear equations is feedback - that is, nonlinear equations have terms which are repeatedly multiplied by themselves." (Briggs and Peat, p 24)

ONE- OVER-F NOISE ($1/f$) - Also flicker noise. One-over-f noise is associated with complex systems, and is characterized by features of all sizes: rapid variations over minutes, and slow variations over years. The signal can be seen as a superposition of bumps (cycles) of all sizes, or equivalently, be seen as a superposition of periodic signals of all frequencies. The strength, or "power", of its frequency component is larger for the small frequencies; it is inversely proportional to the frequency. That is $1/f$. This behavior has been observed in changes in the flow of the Nile, light from quasars, highway traffic, global temperatures, and any other complex system.



OPEN SYSTEMS - involve a continuous exchange of energy and/or information with the environment.

PERIOD DOUBLING - (see Bifurcation)

PHASE SPACE - A mathematically constructed conceptual space where each dimension corresponds to one variable of the system. Thus, every point in state space represents a full description of the system in one of its possible states, and the evolution of the system manifests itself as the tracing out of a path, or trajectory, in state space.

In phase space the complete state of knowledge about a dynamical system at a single instant in time collapses to a point. That point is the dynamical system - at that instant. At the next instant, though, the system will have changed, ever so slightly, and so the point moves. (Kellert, p 7)

POSITIVE FEEDBACK (loop) - when the output of a system is fed back into the system resulting in out of control amplification of the effect.

POWER LAW DISTRIBUTION - a distribution of events such that small events are common and occur frequently, while large events are not common and occur infrequently.

Graphed on log-log graph paper the distribution of such events is a straight line.

RECURSIVE - Said of a system in which the output becomes the next input.

REDUCTIONISM -

1. The analysis of complex systems by breaking them down into their component parts and understanding the parts.
2. The scientific world view which attempts to explain complicated systems in terms of internal simplicities. (p 180)

SELF-REFERENCING SYSTEM - a system in which the output is the starting point of the next step.

SELF-ORGANIZED CRITICALITY (SOC) - term coined by Per Bak for the theory of complex systems which self evolve to the critical state where evolutionary change is possible.

“The basic picture is one where nature is perpetually out of balance, but organized in a poised state - the critical state - where anything can happen within well-defined statistical laws.” (Per Bak, 1996, p xi)

SENSITIVE DEPENDENCE ON INITIAL CONDITIONS - (see Butterfly effect)

1. "Lorenz spelled out the consequences of his discovery as follows: 'It implies that two states differing by imperceptible amounts may eventually evolve into two considerably different states. If, then, there is any error whatever in observing the present state - and in any real system such errors seem inevitable - an acceptable prediction of an instantaneous state in the distant future may well be impossible.'" (in Kellert, p 12)
2. A form of instability where a slightly different set of initial conditions produces instability such that the states of two systems, which initially were extremely similar, rapidly diverge. (Kellert pages 11-12)

STRATIFIED STABILITY - a term coined by Jacob Bronowski referring to a dynamical (open) system which is stable at a particular level of complexity.

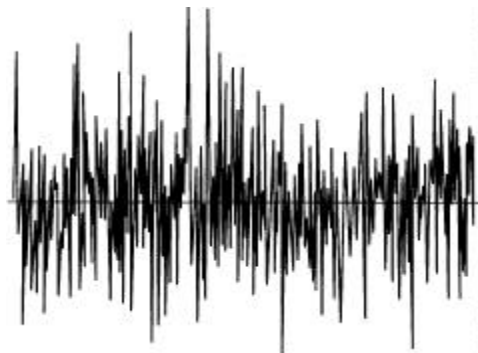
An integral part of the theory is the idea that such systems are self-evolutionary through a series of stratified stabilities beginning simple and becoming progressively more complex. Because these evolving systems are dissipative structures they evolve according to those principles.

TIME SERIES - A clock ticks as it counts out the seconds, one, two, three, . . . We can use this timing to measure out things - values as a function of time.

UNIVERSALITY - the principle that the underlying properties and behaviors of a large class of problems are essentially the same, and therefore, can be studied in principle without delving into the particular details of each system. The resulting analyses, however, can be applied to the understanding of any system which possesses those properties.

“We hope that important features of large-scale phenomena are shared between seemingly disparate kinds of systems, such as a network of interacting economic agents, or the interactions between various parts of the crust of the earth. This hope is nourished by the observation of the ubiquitous empirical patterns of nature - fractals, 1/f noise, and scaling of large events among them. Since these phenomena appear everywhere, they cannot depend on any specific detail whatsoever. . . this gives the option of selecting the simplest possible system belonging to that class for detailed study.” (Bak, 1996, p 43)

WHITE NOISE - Random, or white, noise is a signal in which there are not correlations between the value of the signal from one moment to the next. The white noise pattern shown has no slow fluctuations, that is, no large bumps. White noise sounds like the hiss on the radio between stations rather than the music.



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