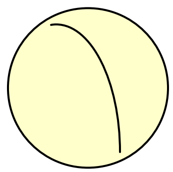
１. Object of analysis of complex system

１. １　What is complex system ?

（１）Life



Embryo or disordered thing

Ordered structure

Phenomenon formed autonomously

- Longtime phenomenon

  Evolution, Origin of living thing

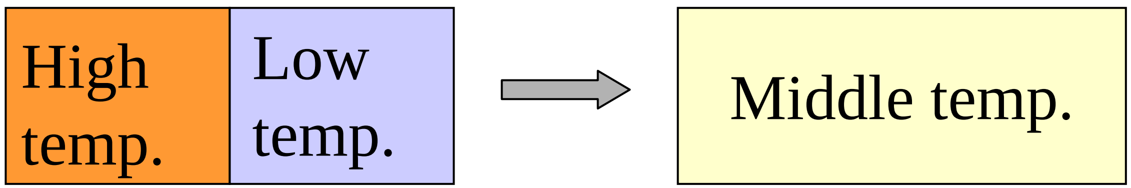
(2) Traditional science

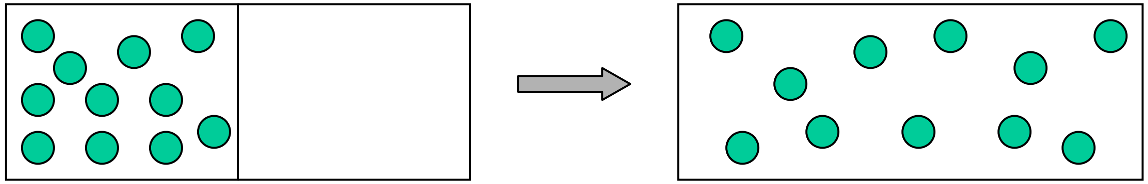
Close and thermal equilibrium system

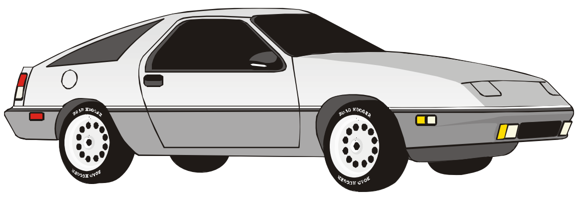
In irreversible process,

"order → disorder" or enlargement of entropy

"thermal death of universe"







brake

Thermal energy

Kinetics energy

[traditional science]

determinism of classical mechanics,
probability theory of statistical mechanics

↓

linear, superposition, reductionism

↓

“devil of Laplace”

Results arise self-apparently from initial conditions and governing equations.

↕

However in practice,

probabilistic behavior（Brown dynamics due to fluctuation，quantum fluctuation）, chaos in which marginal difference of initial conditions generates significant difference of results（nonlinear dynamics）, self-organization from disordered states（non-equilibrium thermodynamics）etc

These are contrary evidence to traditional science.

（3）Definition of complex system

（1）aggregation
（2）non-linearity of local interaction between components
（3）open system（flow of material and energy in/out of environment）
（4）non-equilibrium

Non-linear interactions can make the collective behavior of an aggregate different from what we would expect from simply averaging the behavior of the components.
Notability is not “existence”, but “emergence” and/or “generation.”

⇕

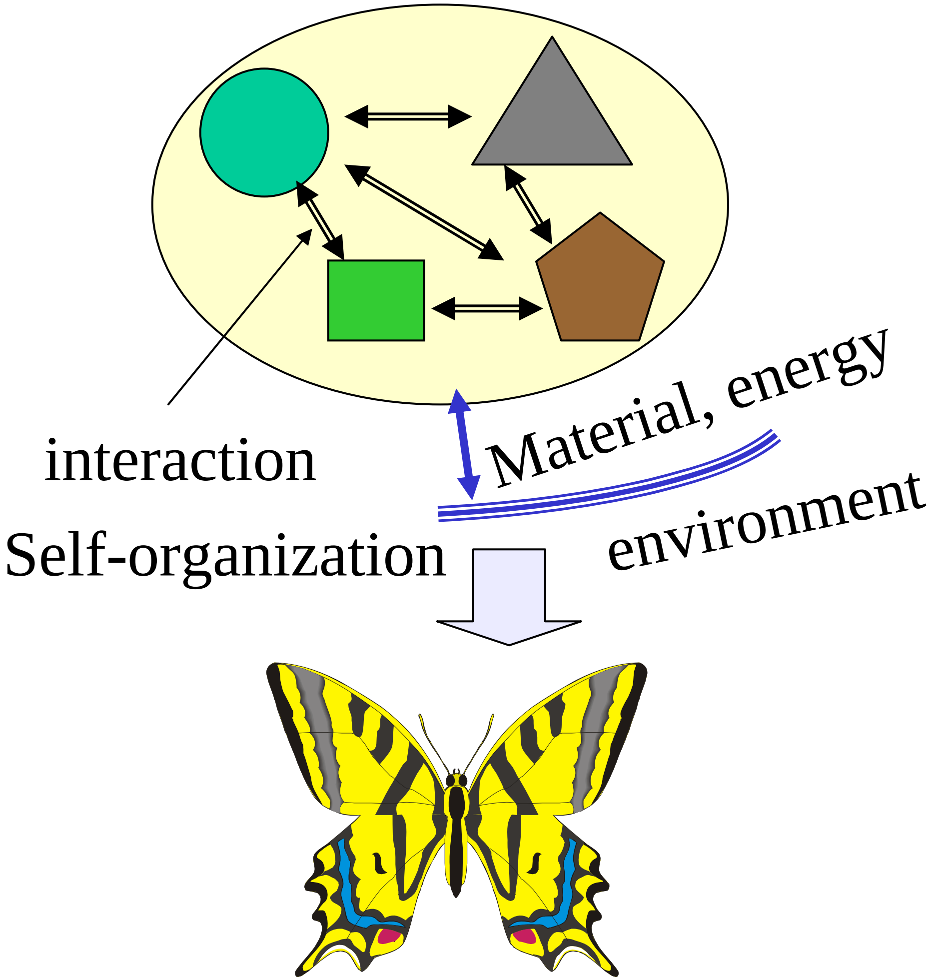
Traditional science
reductionism：　linear thinking(understand behaviors of components, and enlarge overall the whole system.

How an ordered structure is generated from a state of a complex and disordered material ?

Dissipative structure： When the flow of energy and material between the system and environment reaches a critical value, new structure and organization which have never happened before are generated self-apparently based on a nonlinear interaction.
This particular feature is kept only by the dissipation of energy in a nonequilibrium, nonlinear and open system.

Self-organization = generation of dissipative structure

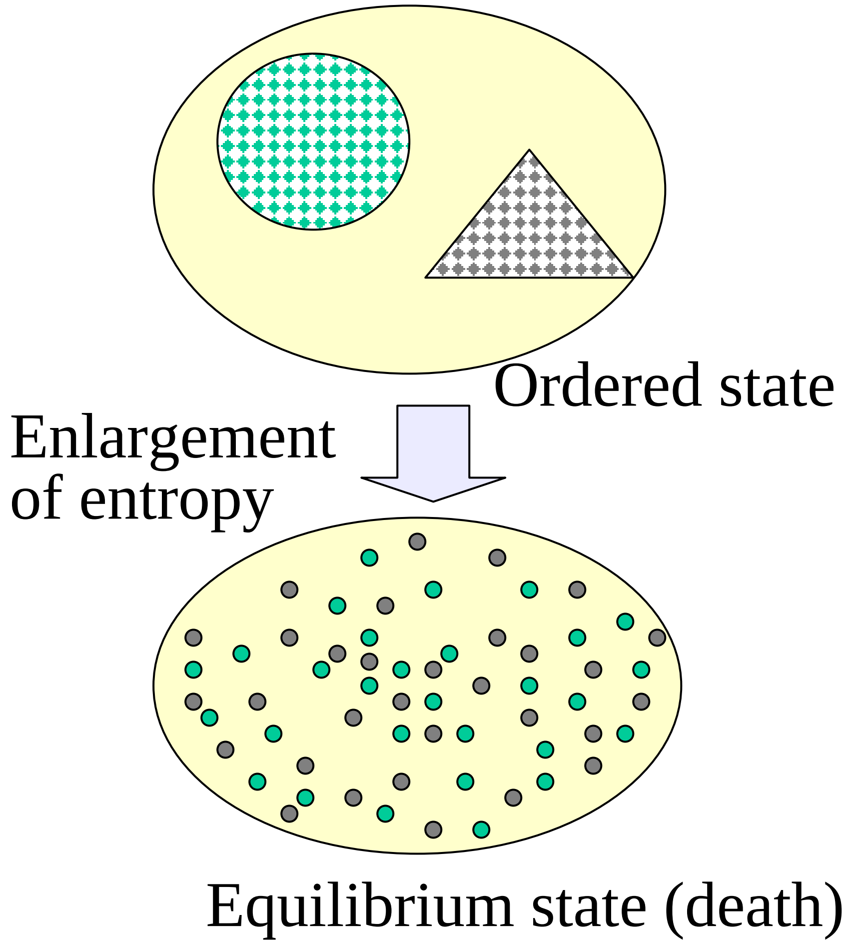
Complex system science



Method of analysis: Algorithm, simulation

Object : Information, procedure

Equilibrium thermodynamics



Principle of energy and entropy, Differential equation

matter

（4）What is a system?

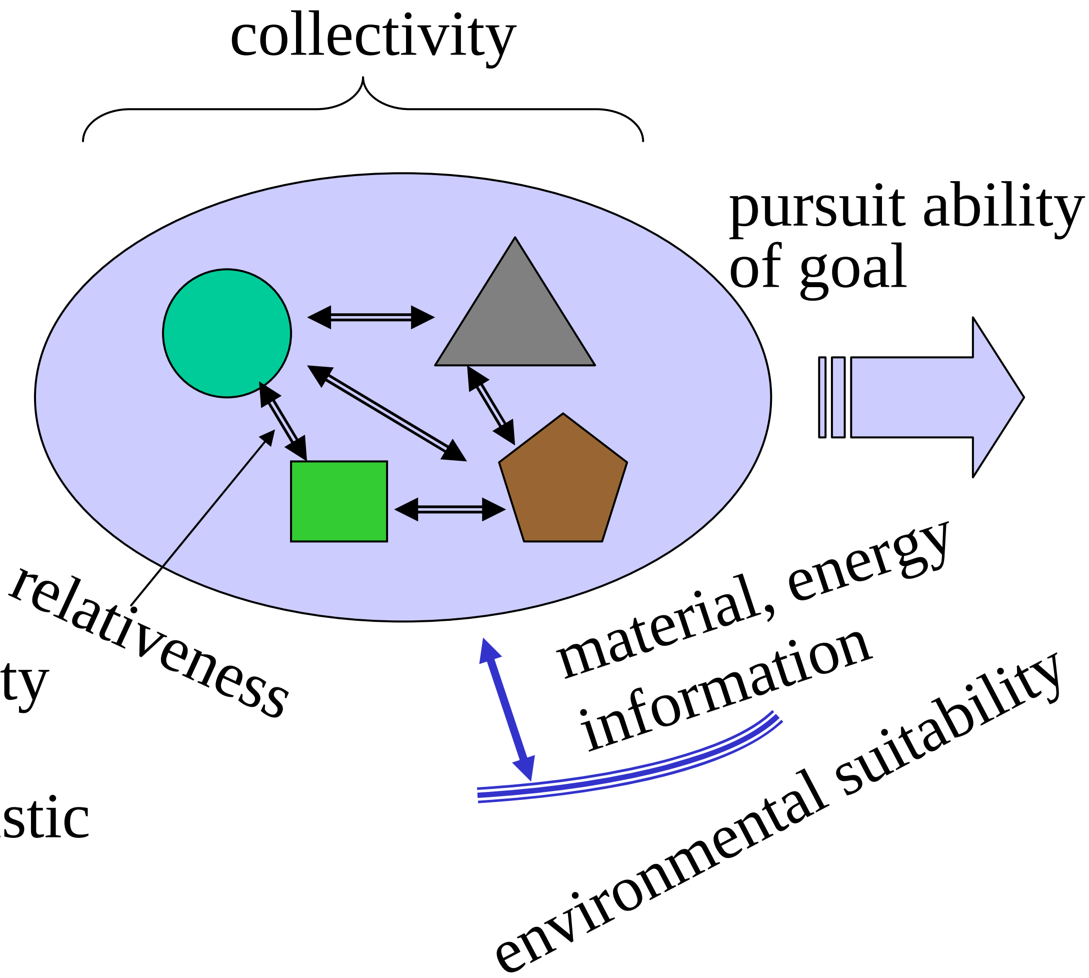
[4 features of system]

1．collectivity

2．relativeness

3．pursuit ability of goal
objective, goal/target

4．environmental suitability
environment
environmental characteristic
⇔ system characteristic



When environment changes, existence of the system keeps.

Adaptive system： the optimal state keeps always even if environment changes

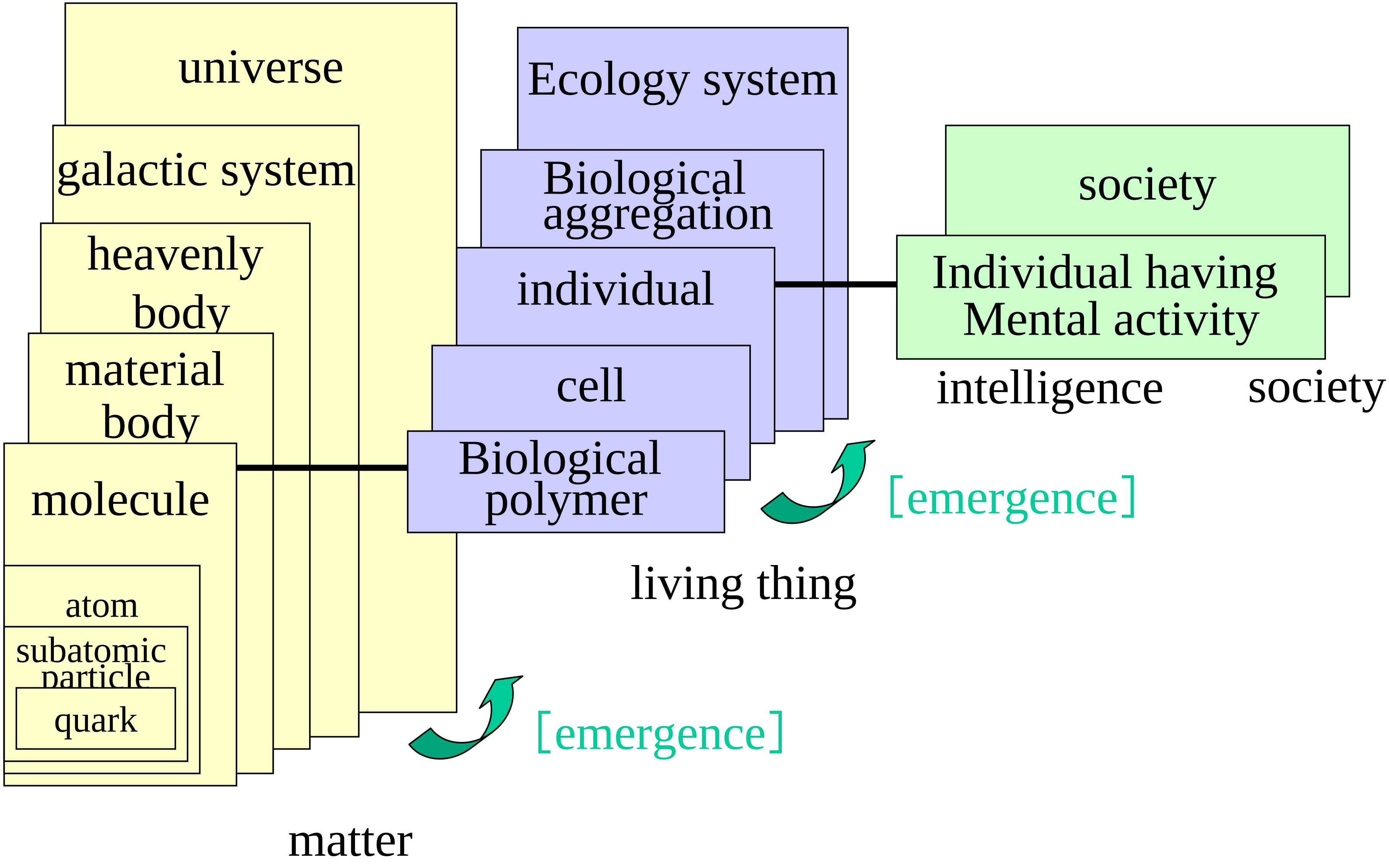
Self-organizing system： Both internal structure and function change.

［essential quality of system］

Synergy effect： Optimization of an overall system is much more than the summation of localized optimization of all components.

Total system： individuals（module, hollon） stand alone.

(5) Hierarchical structure of complex system



(6) Examples of complex system

(a) Chemistry:　Formation of a new molecular by many molecular connecting in chemical reaction

(b) Animate being

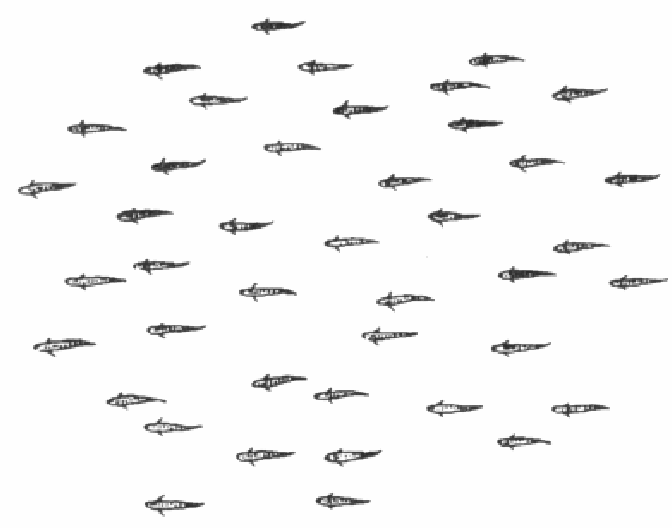
Cell is built up from complex cell membrane nucleus and cytoplasm, and each element is built up from many further minute elements.

Several tens or several thousands metabolic processes are promoted simultaneously and regularly in a cell.

Animate organs are built up from many organs which act regularly and cooperatively.

(c) Ecological system

Animate beings construct an animal society which consists of many individuals.



(d) Nerve

A human’s brain consists of more than 10^{10}neuroral cells and is a most complex system.

(e) Engineering

Automobile engine, overall factory system, Electric power plant

(d) Others

Economical activity, Society, Computer

１．２ Self-organization

A self-organization in dissipative dynamical system is a phase transition in a thermal nonequilibrium and irreversible constitution. A pattern of macro phenomenon originates based on nonlinear and complex cooperation. At that time an interaction energy between the dissipative dynamical system and circumstance reaches a critical value. Stability of a creative structure keeps on a balance of nonlinearity and dissipation.

[Phase transition]
A change occurs abruptly in narrow temperature range.
phenomenon which change over between different ordered situations.
Generation of material comes from symmetry break
[Phase]
It has uniform structure.

timewise： rhythm construction, spatial: pattern construction

［feature of self-organization］

▪ autonomic, autonomous, self-generating, automatic and spontaneous order formation
▪ free and self-controlled structure by formation of intrinsic rule
▪ self-controlled system, self-generating order, self-organizing structure

［self-organized criticability］

▪ analogy of critical phenomenon in phase transition
  ＝ universal nature
▪ behavior of material system at critical state

［emergence］

▪ emergence of macro-structure in higher level by local interaction with constitutive elements in lower level
▪ unique phenomenon in complex system (non-equilibrium and nonlinear system), emergence of unforeseen organization, structuation and pattern

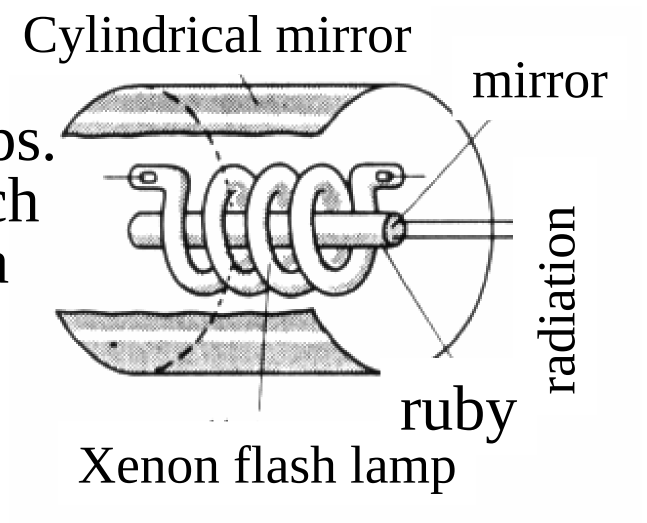
１．３ examples of self-organization

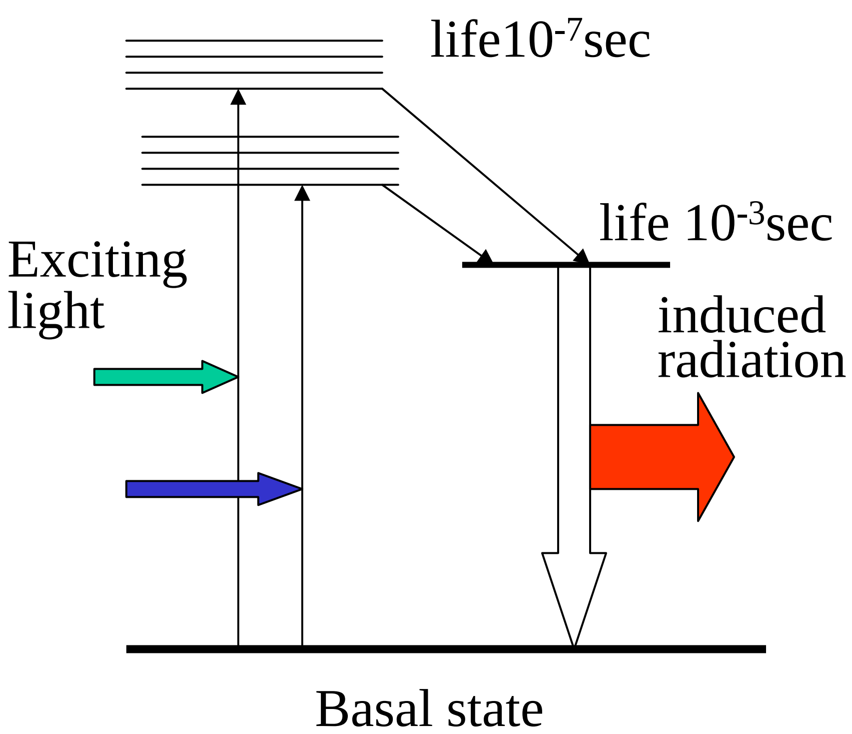
Complex system is interdisciplinary associated with many areas, such as “quantum mechanics, fluid dynamics, chemistry, biology, economics, sociology, neurology, artificial intelligence.”

１．Quantum physics： laser（photon，phase transition ）
２．Fluid dynamics，aerology，geology： Taylor instability, Benard instability（phase transition）
３．chemistry： BZ reaction（phase transition）
４．biology： bimolecular，biocell，biological aggregation （phase transition，evolution）
５．economics： economical system（mechanism of market）
６．sociology： society（history）
７．neurology（psychology）： brain（neuron-cell，cognition）
８．Artificial intelligence： neural network（learning algorithm）
９．Solid physics： Gunn oscillator（pulse，chaos）
１０．Mechanical and aerospace engineering： buckling pattern, flutter
１１．Electric and electronic engineering： nonlinear oscillation

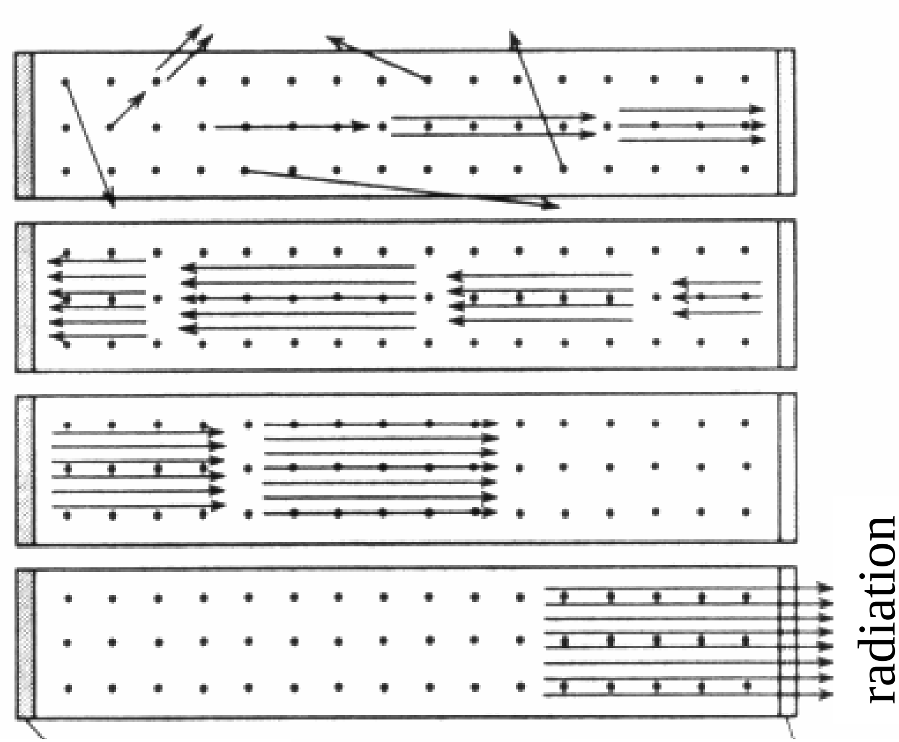
(1) Laser

Pumping weakly causes them to act like lumps. The atoms emit photons independently of each other, giving rise to incoherent light. Above a certain pumping threshold, however, the internal atomic dipole moments become ordered, giving rise to extremely coherent 'laser' light.





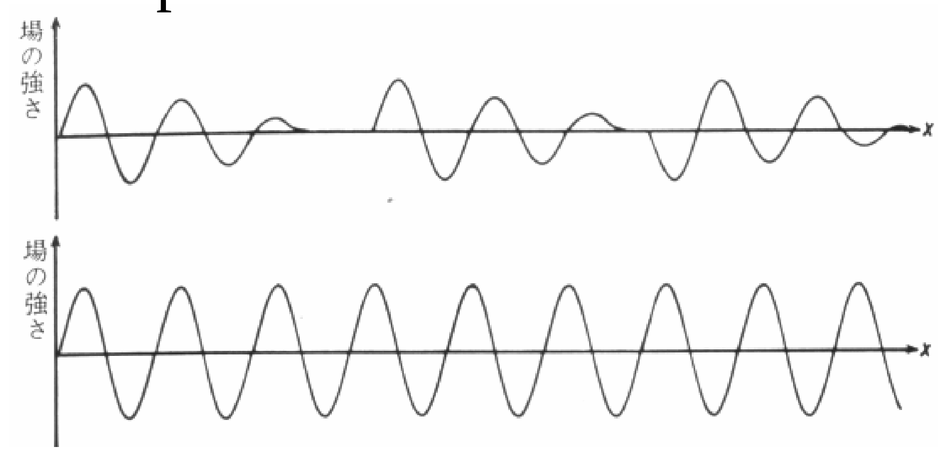
Principal of laser radiation

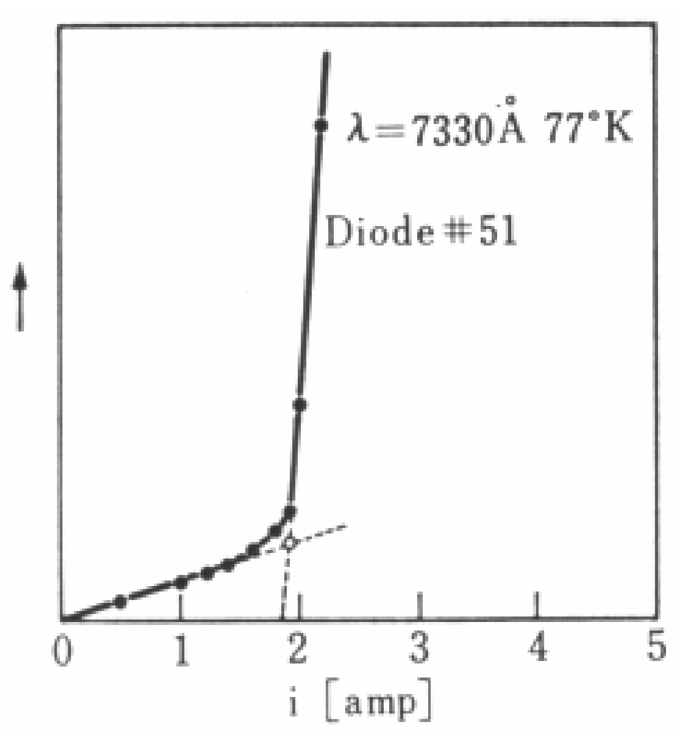


At the start of such a transmission, many different wavelengths of light are present. A slight preference for a particular wavelength progressively aligns ('enslaves') excited electrons so that they emit light at a single wavelength. At a critical point this process cascades, resulting in high intensity, coherent output from the laser.

Wave emitted from lamp

Laser wave





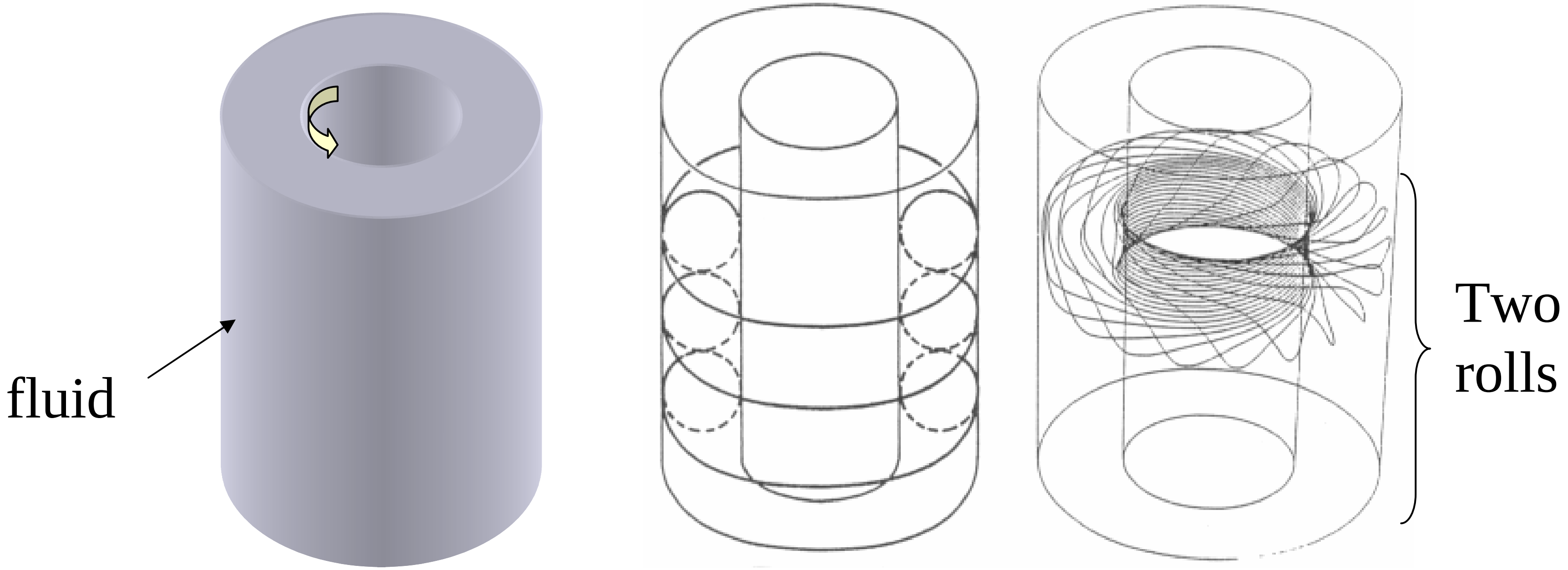
at small exciting light：light length＝3m

When injection energy goes over critical value

→ new phenomenon occurs

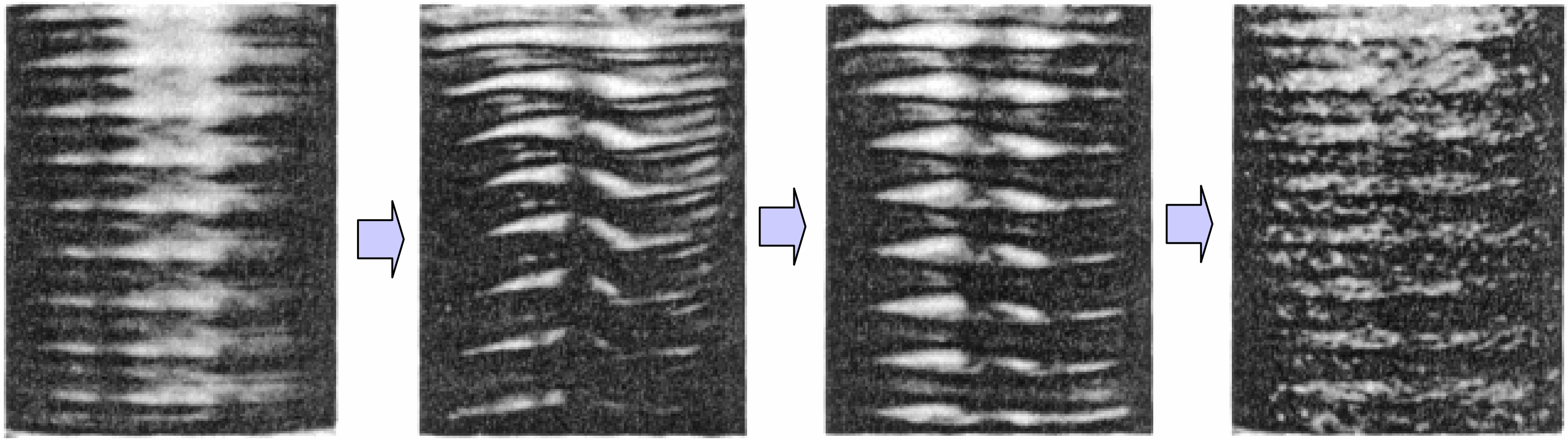
one big wave with length of 300,000km ＝ laser

（2）Taylor instability（Formation 1 of fluid dynamics pattern）

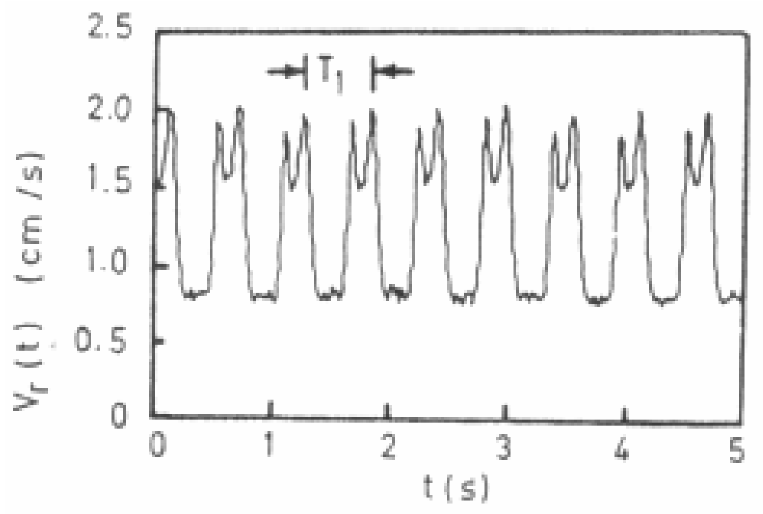


Slow revolution：　coaxial stream line（inner cylinder sets up fluid flow through friction）

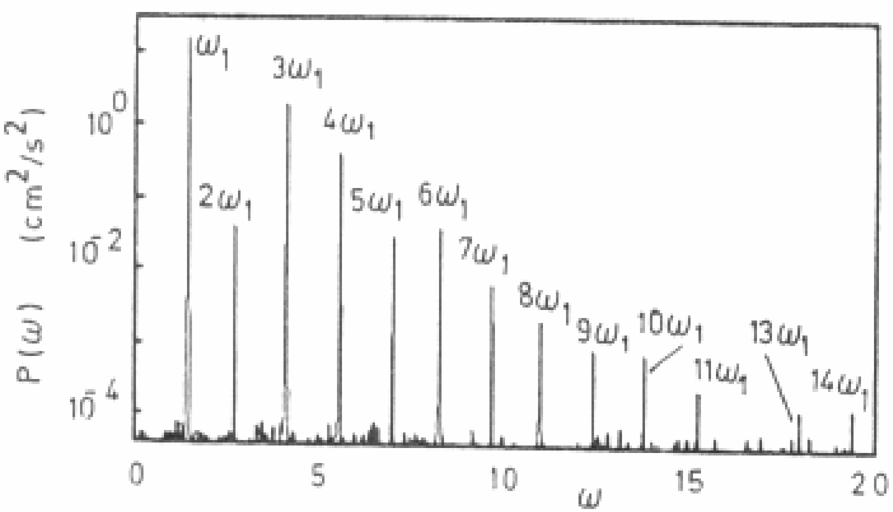
Faster revolution：　new type of movement＝roll mode



Formation of role | a oscillation | complex oscillation | chaos



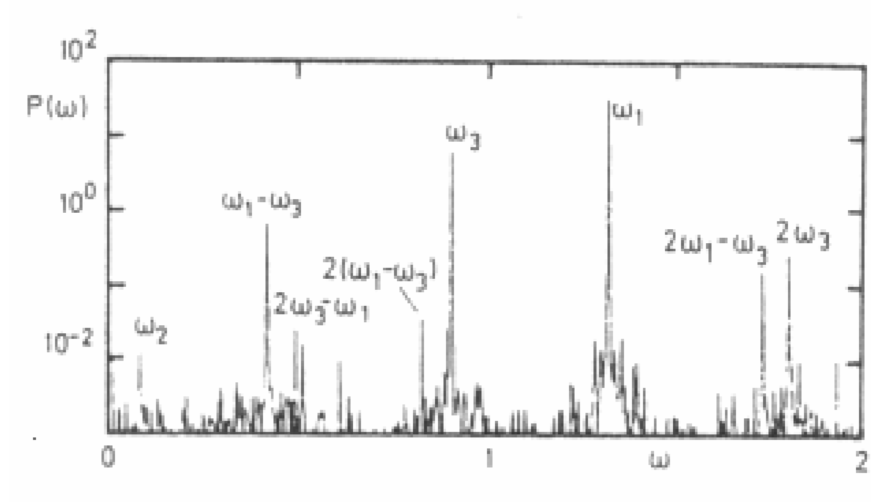
radial component of local speed
（measured by laser Doppler speed meter）

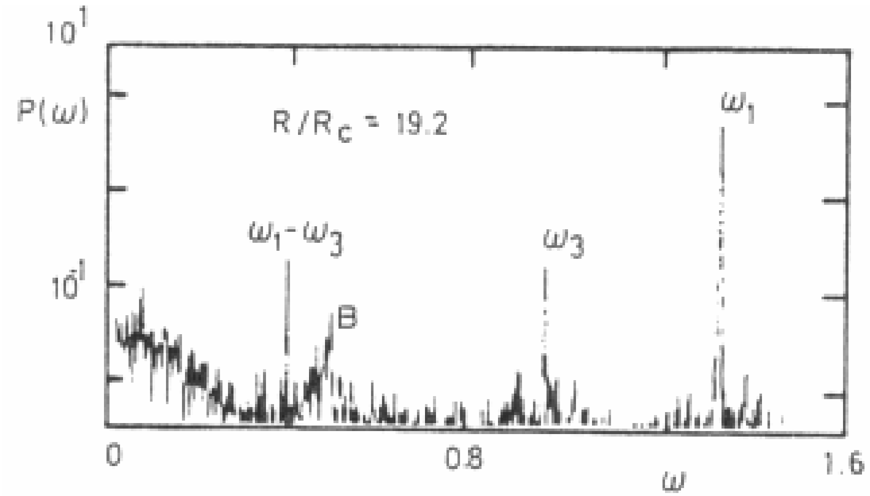


Power spectra
（periodic duplation）

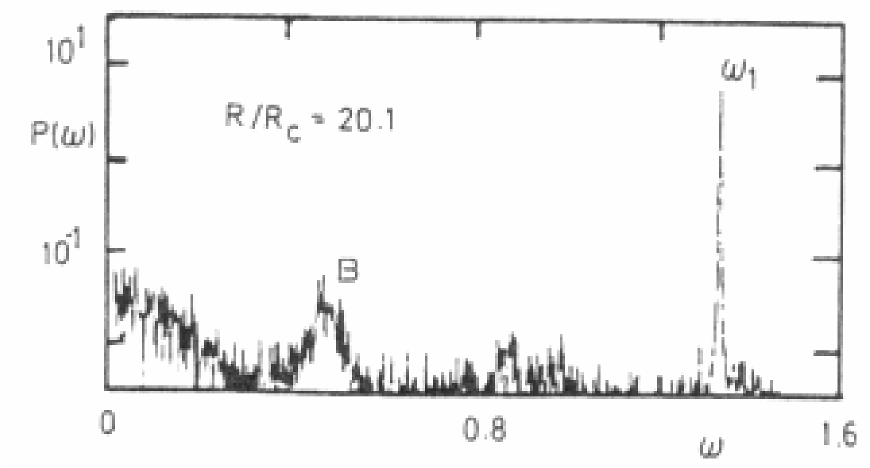
Power spectrum of radial speed

(Basic frequency ω_1, ω_2, ω_3 and their linear connection)





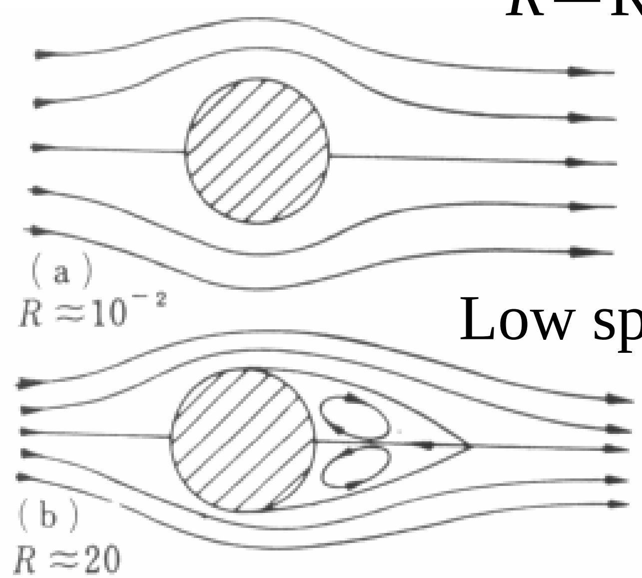
extinguishment of ω_3 at R/R_c=19.7~19.9



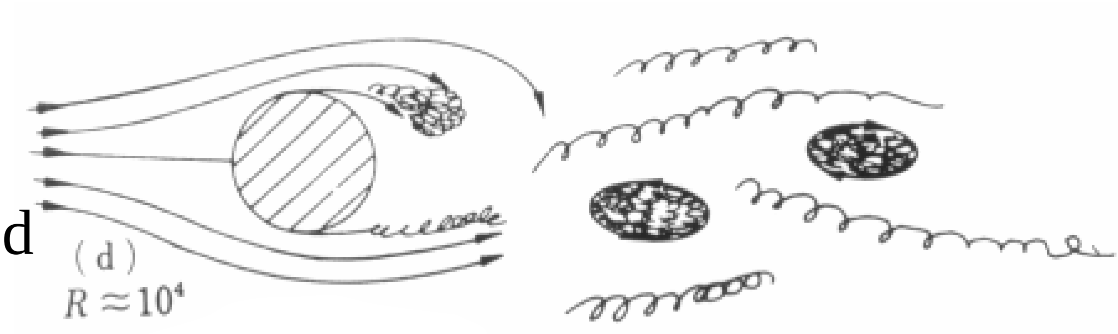
- emergence of unique characteristics in self-organization system
- hierarchy of patterns

(3) flow around a cylinder

R = Reynolds number = inertia / viscosity

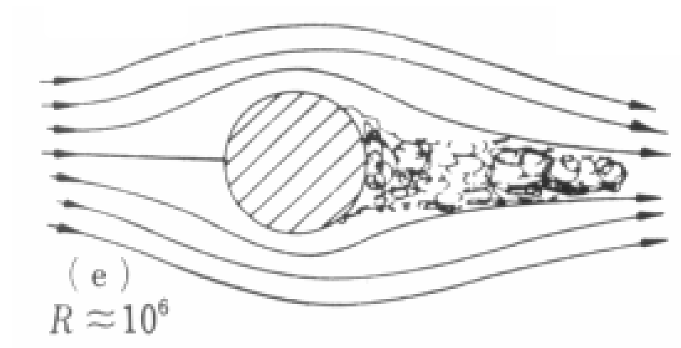


Low speed

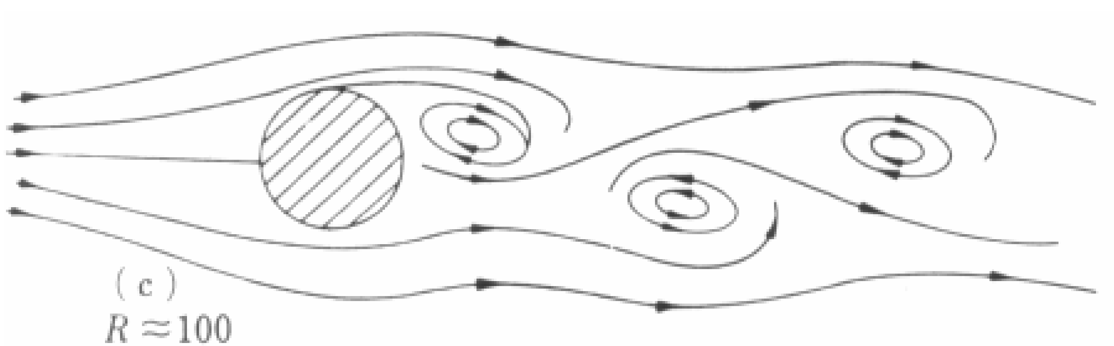


Beginning of turbulence

Static pattern: a pair of eddies

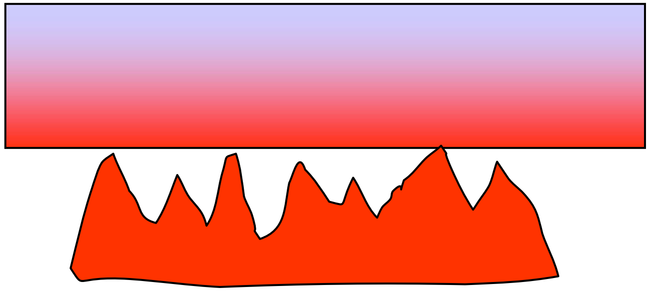


turbulence



Dynamic pattern: eddy oscillates (Karman eddy)

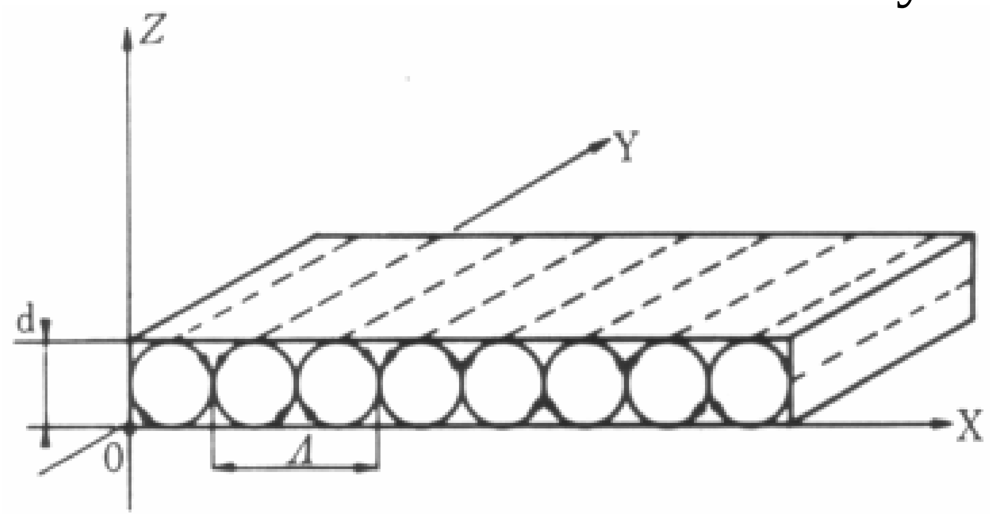
(4) Benard instability (convection instability)



Heated from beneath
At low temperature gradation
heat transmits due to conduction,
fluid body stands still

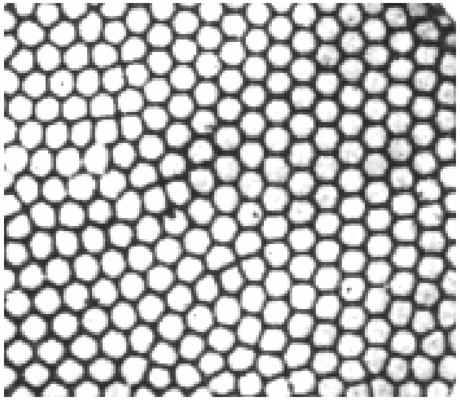
When temperature gradation reaches critical value
Benard convection starts
heated particle in beneath expands and floats,
cooled paricle in surface

Ordered : roll or honeycomb

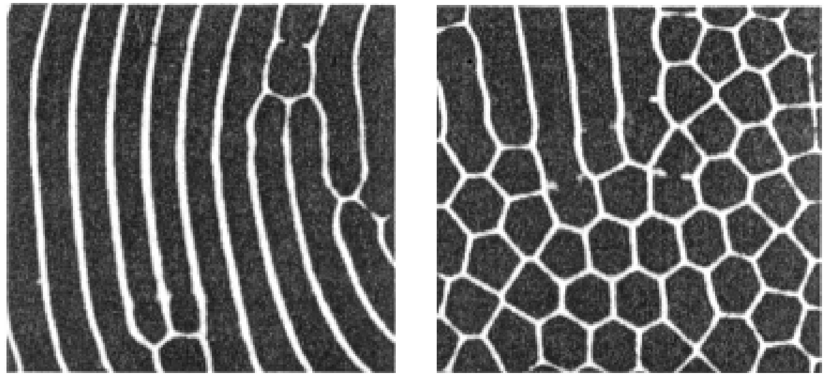


Completely uniform state
↓
Ordered space pattern

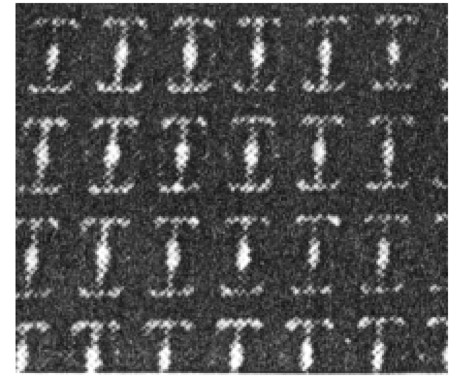
Aerial view



Honeycomb shape



Mix of roll and honeycomb shapes

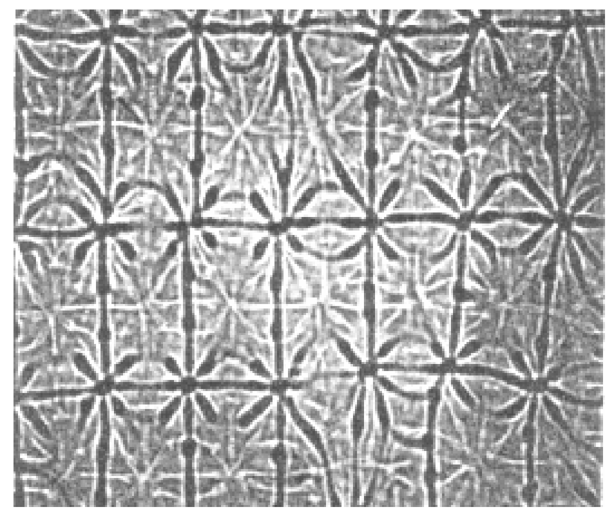


Two pairs of roll shapes

New phenomenon arises at larger temperature gradation.

waved movement along roll axes

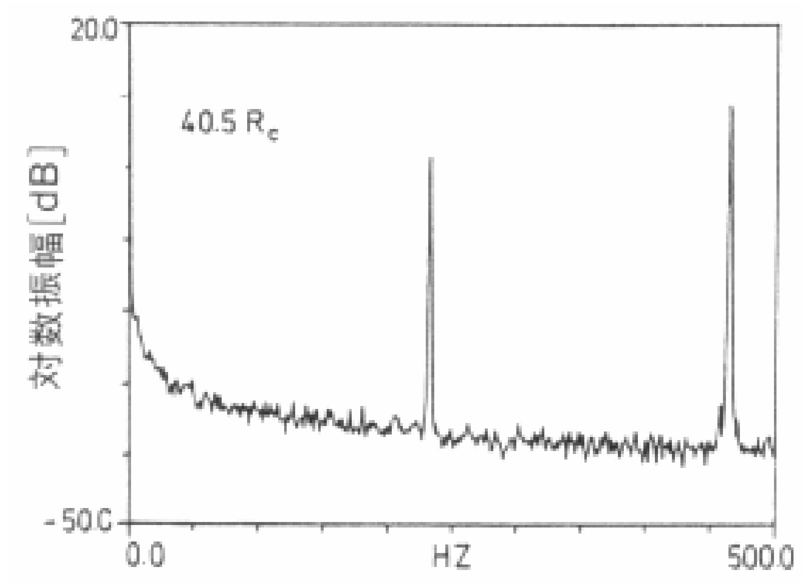
→ spork-like pattern oscillates temporary

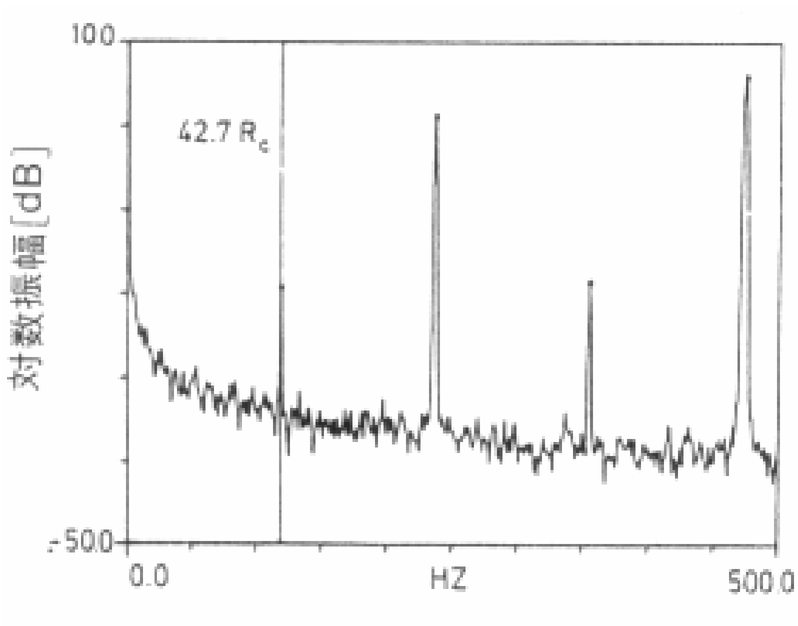


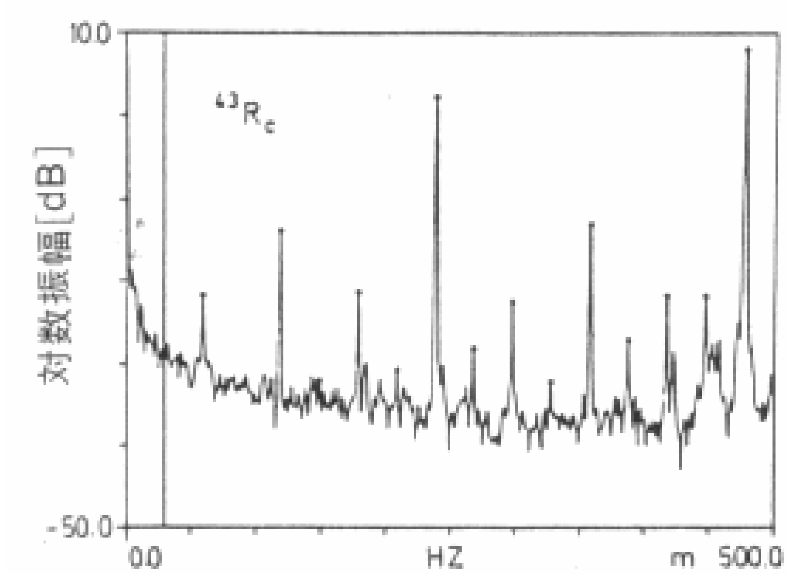
- periodic duplation

As Rayleigh number (measure of natural convection) increases, period increases twice its amount repeatedly at fixed Rayleigh number.

Finally turbulence or chaos are generated.







Benard instability → determines air motion and generation of cloud

Taylor instability, Benard instability

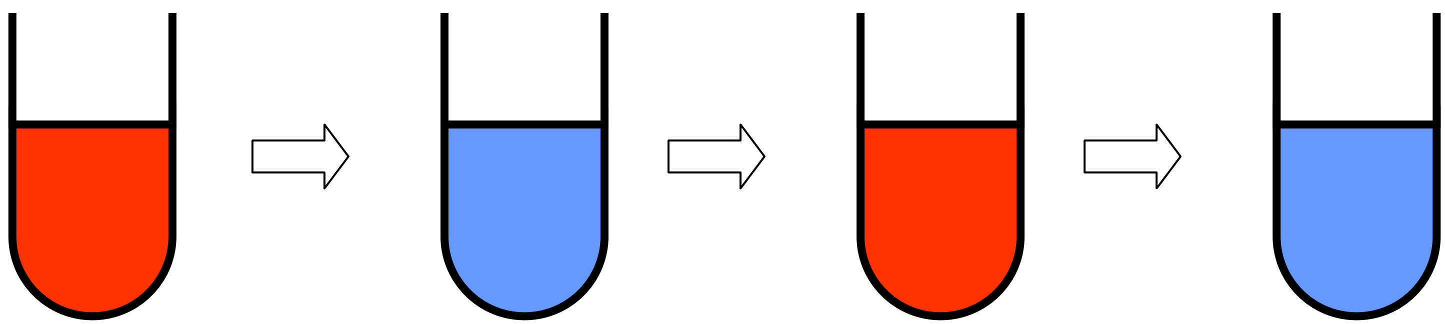
flow pattern of fluid and/or gas movement around moving body, such as car, airplane and ship

（5）Belousov-Zhabotinsky反応

BZ reaction is typical example in many spatial and temporal patterns in chemical reaction.

Solution which consists of $Ce_2(SO_4)_3$, $KBrO_3$, $CH_2(COOH)_2$, H_2SO_4 and is admixed by a few drops of Ferroin (oxidation-reduction indicator) is stirred well.

⇨ Color changes periodically（rhythm）



Ce^{3+} excess　　Ce^{4+} excess

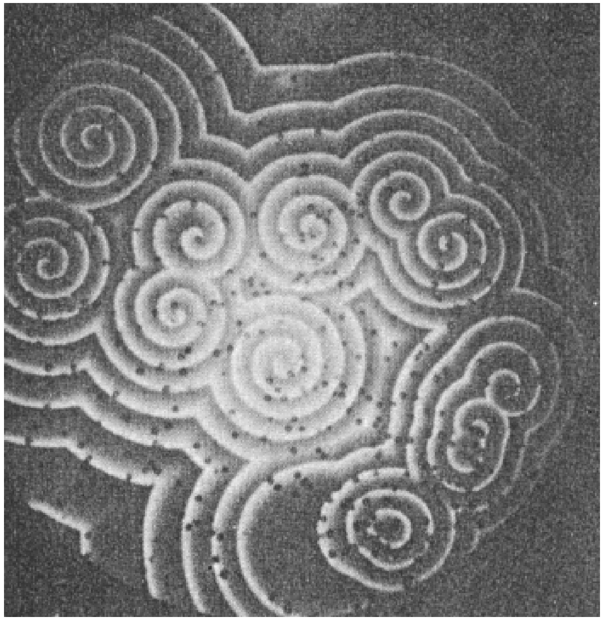
［space pattern］

When reaction is proceeded in a thin flat petri dish, a wave pattern transmit with a constant rhythm for the first time, oscillation in overall petri dish → Space pattern forms for the last time.

・A heart is open system and beats in the fashion of a pattern similar to BZ reaction. Sudden death of irregular heartbeats corresponds to a transition that a pattern of concentric circle (constant heartbeats) changes to a spiral pattern in heart muscle.

・ natural pattern（space pattern observed in growth of plant and/or animate thing.

Patterns of zebra and shell

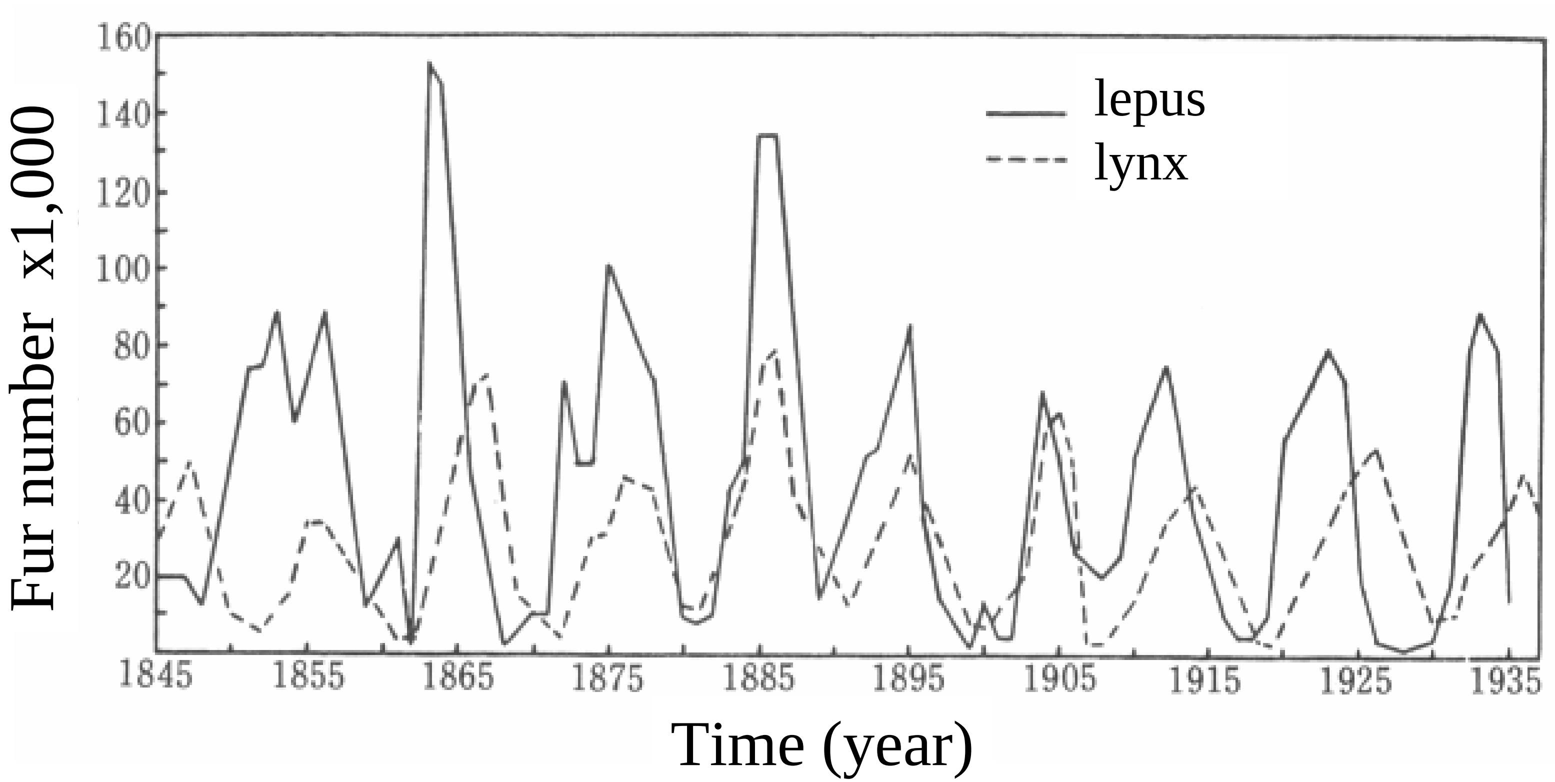


(6) biology (autecology)

population change with time in predetaor (lynx) –prey (lepus) relationships.

Lotka-Volterra equation $$\frac{dx}{dt}=x(\alpha-\beta y),\ \frac{dy}{dt}=-y(\gamma-\delta x)$$

⇒ ①stable pattern, ②complex oscillation (limit cycle), ③chaotic behavior



(7) life cycle of monophosphate

oscillation of mechanism of cAMP(cyclic Adenosin 3’ 5’ Monophosphate)

Dictyostelium disciodeum

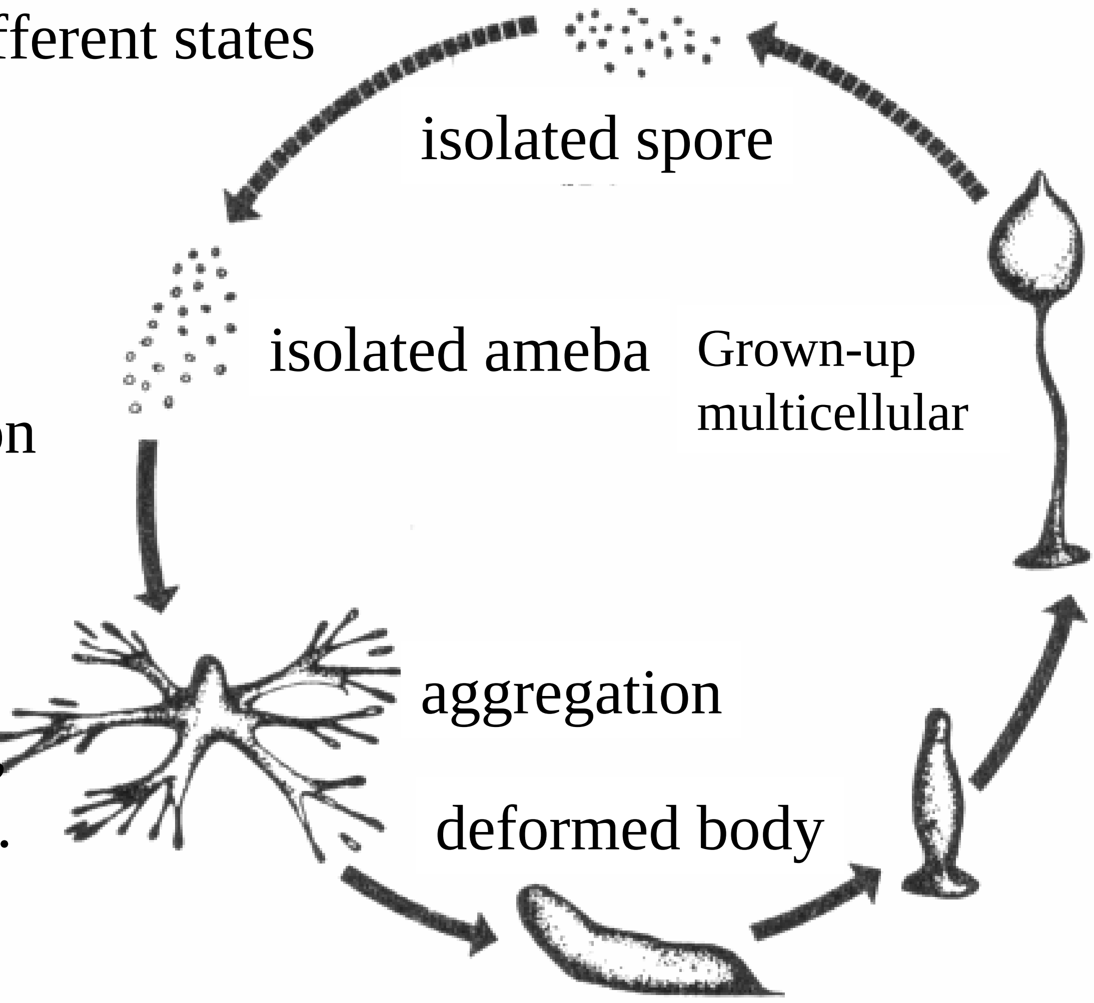
Transition between two different states

Ameba is an independent individual cell.

↓

Facing risk of starvation,
They transit to aggregation
→ multicellular living

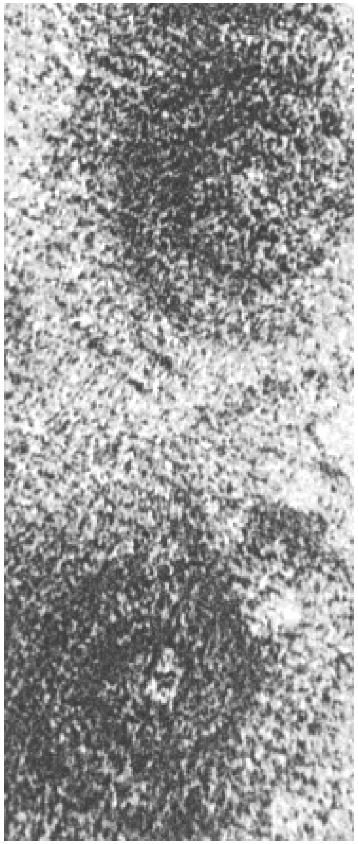
Aggregation of cells
polar globules are formed,
specialized and cooperative.
(cell of spore and stalk)

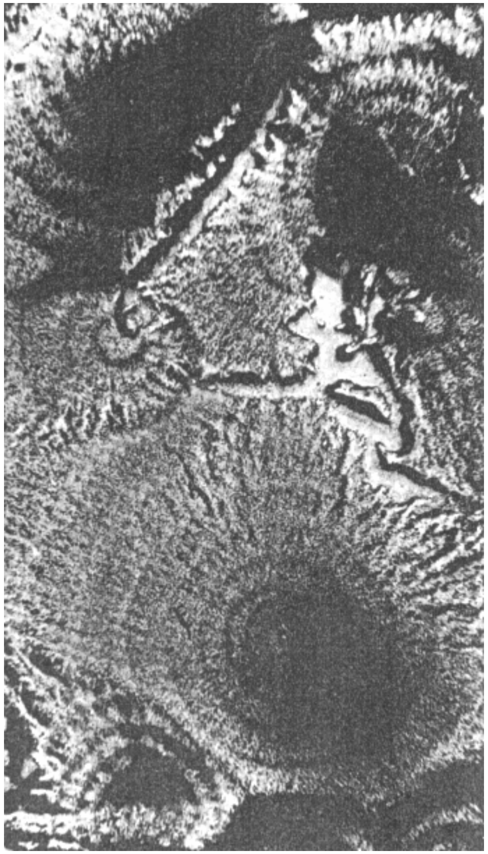


Each staving ameba reacts to cAMP which emits from the center, and gathers to the center such as concentric wave pattern concentrates.

Cell aggregation process＝ self-organizing due to instability state

・ control parameter
Allowance of food to critical value





(8) growth of nerve network

Difference of intelligence: difference of self-organization degree of a brain

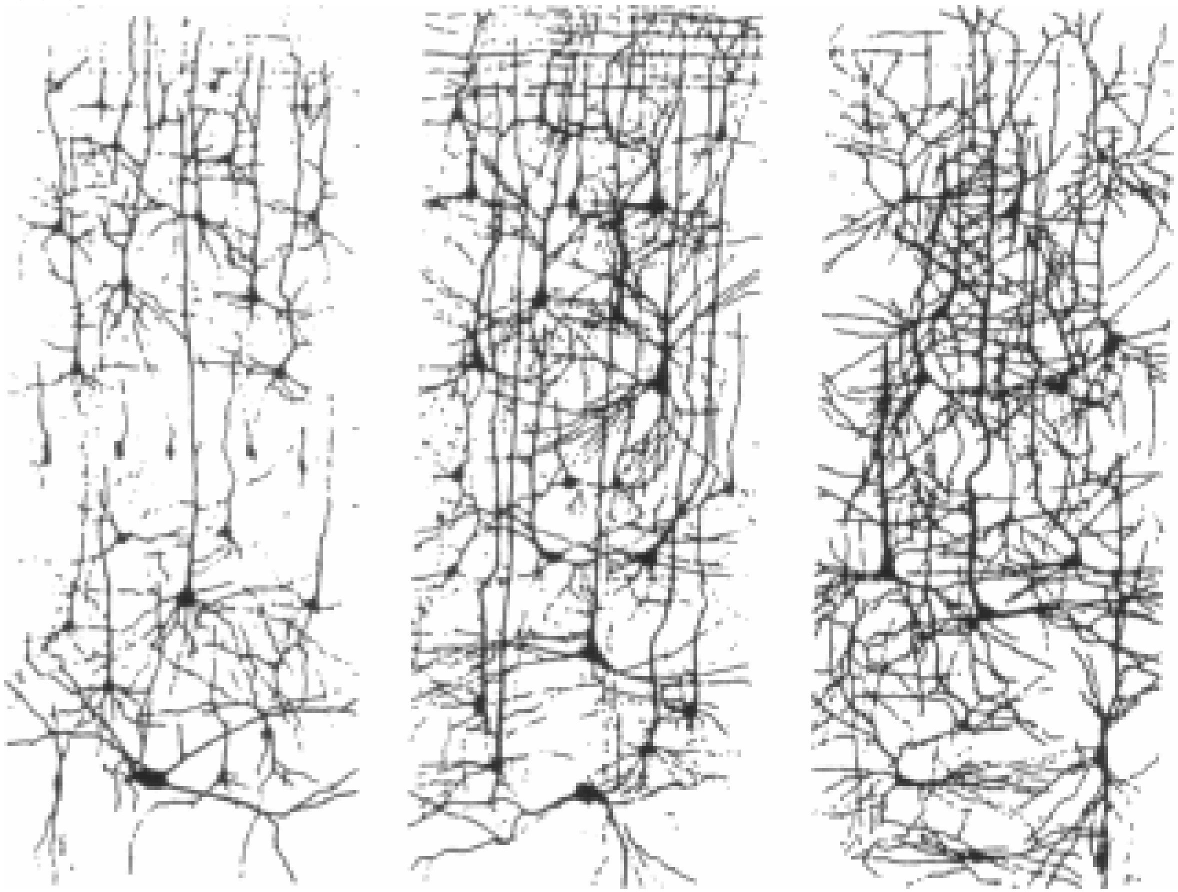
Growth of brain = Connection of nerve cells becomes intimately-united

weight of brain

Just after birth 400 gr

6 months old 800 gr

10 years old 1400 gr (same of adult)

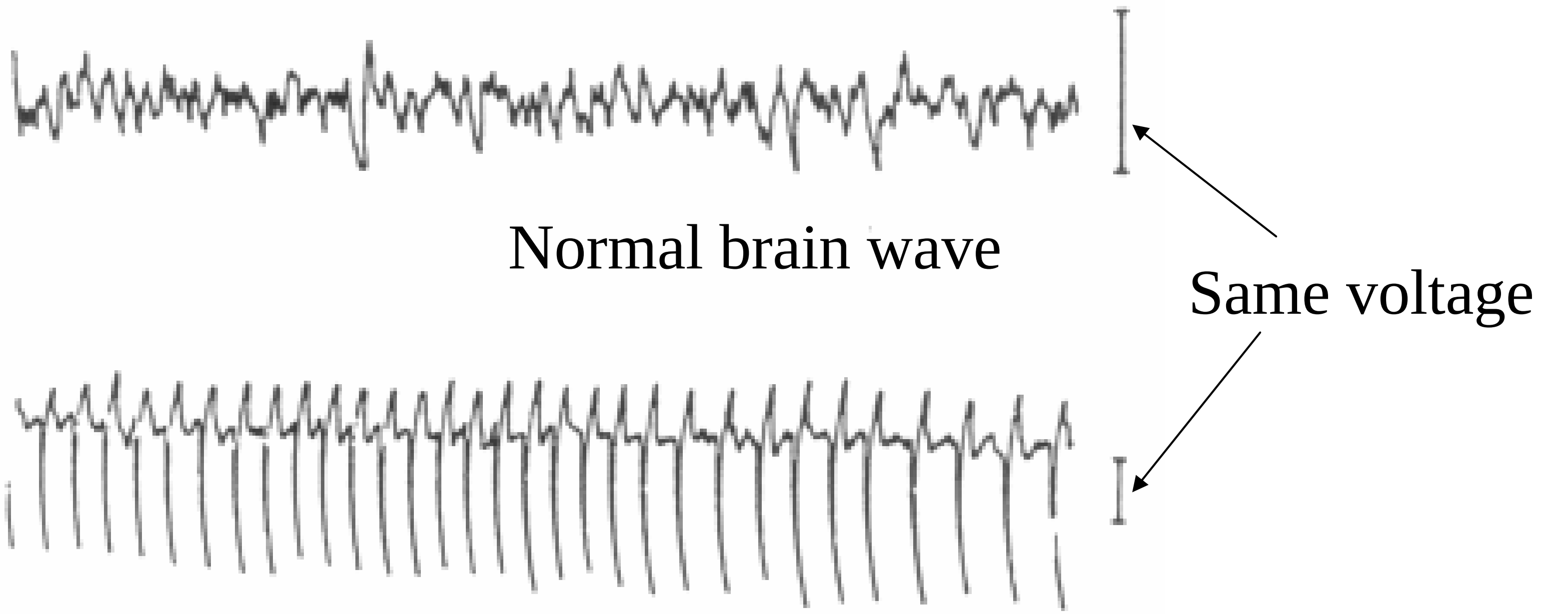


3 months after birth 15 months 24 months

(9) brain wave (oscillation in animate thing)

- An animate thing has various highly ordered and highly functional structure
- Individual components cooperate in high degree.

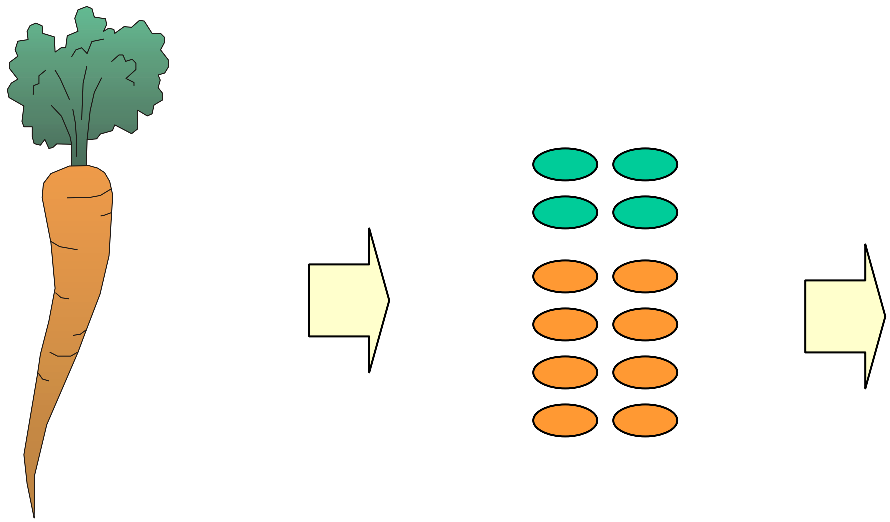
Brain wave = electric oscillation in brain

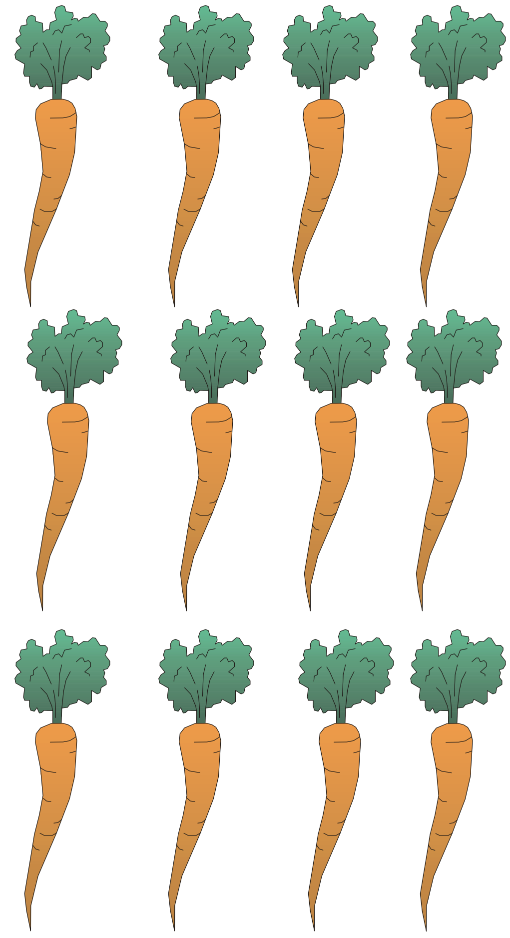


Brain wave at epileptic seizure

- muscle contraction, generation of electric voltage in an electric fish, recognition of pattern, conversation

(10) Morphology genesis





A carrot is divide to each individual cell.

Complete carrots are reproduced from any cells.

- Every cells have complete information by which complete organization can be firmed.

Almost all cells of almost all multicellur organism include same DNA.

[from unspecialized to specialized]

Information about specialization is not given in individual cell, but each cell in an organization obtains an information of specialization from environment.

Information of position is provided by a chemical precursor pattern. When local concentration grows high enough, character gene come into play and cell is specialized.

Cells are different from each other based on a different activated gene.

(１１)Living thing(life)

An important question concerning the origins of life is how essential features of living systems arose during prebiotic, molecular evolution.

Followings are pointed to for features of living thing.

①Each has body, and then he is recognized from others.

②Metabolism, such as exchange of energy and material, is conducted, and then self-sustained growth can be done.

③Self-replication that self generates not-self is carried out and then offspring is left. It happens at each level of gene, cell and entity.

④Mutation, adaptation and evolution are carried out under interaction with environment.

After all life existence is kept through the network connected by many interactions. Essence of life is not material but situation of organization.

When diverseness of molecule increases and its complexity exceeds a threshold value, life phenomenon emerges.

Life comes into existence on the basis of collective behavior of molecule system in which each one interacts together. It emerges as a whole. It always remains in existence as a whole..

Genome system is a complex chemical computer. It is not a serially processing computer but a parallel processing chemical computer in which genes and products act all together.

（12）parallel processing chemical computer（brain， neuraxon）

［brain］

When a brain acts, a neuron signal transmit in pulse. It is an excitation which is a generation of pulsing action potential, individual neuron is an oscillator, that is, CPU. An own natural period is a few millisecond which is far-slow comparing with a few nanosecond which is the clock time of computer generation. However, a computer has only one CPU, but a brain has 10^{10}CPU.

Therefore computing speed is

$1/10^{-9} = 10^{9}$ ／sec in a computer

On the other hand　$10^{10}/10^{-3} = 10^{13}$ ／sec in a brain

[neuraxon]

Overall surface is oscillator.

- Signal pulse is transmitted without distortion or decay.

Connection of nonlinear oscillator

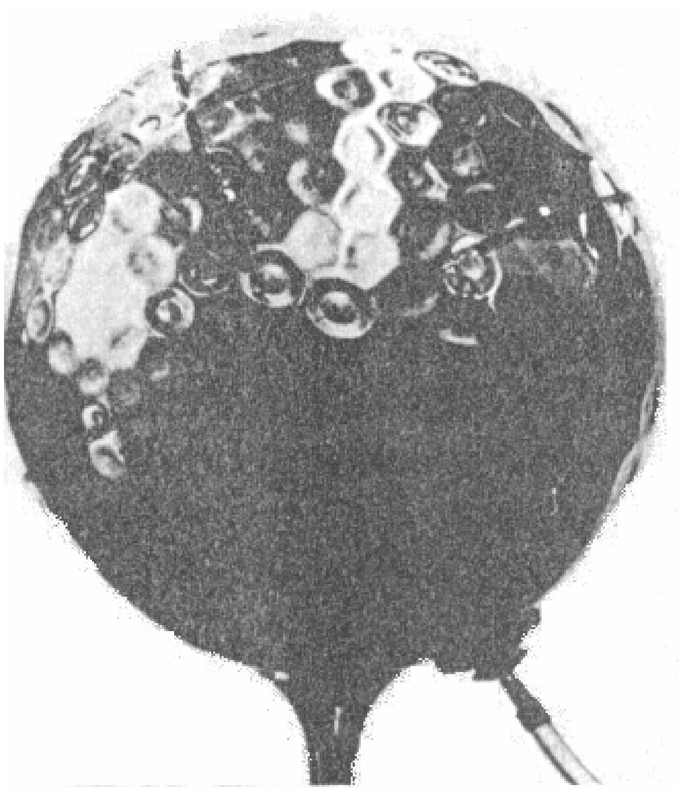
- Oscillators synchronize together and fall into line.

On the other hand, electric signal in electric circuit is distorted and decayed by impedances of R, C, L.

（13）buckling (mechanical engineering)

Drastic change of system due to change of outer parameter

buckling pattern of metal thin shell inside of which is depressurized



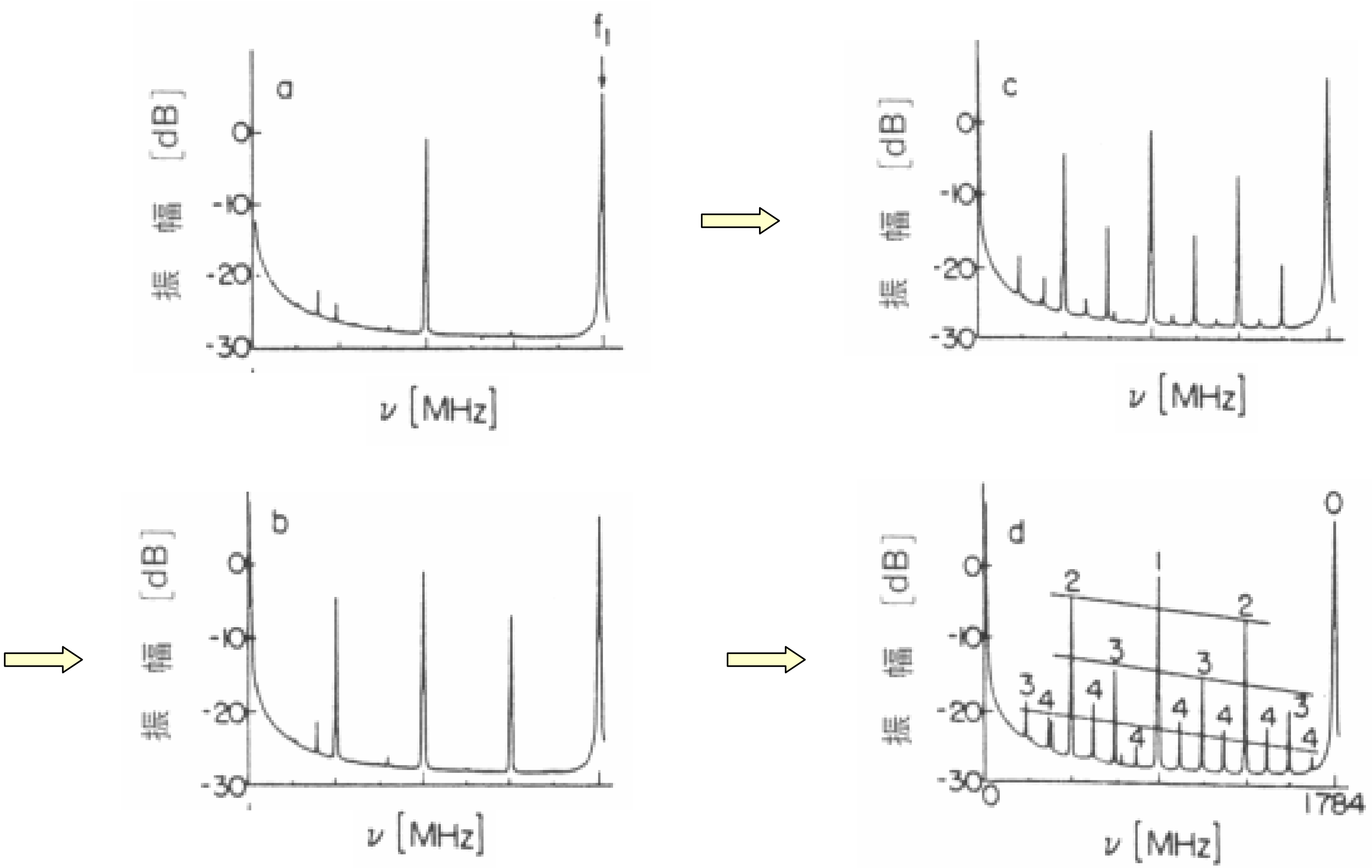
- breakage of bridge when bending or lateral force exceeds over the critical value.

dynamic

flattering of airplane wing

（14）nonlinear oscillation in electric circuit

- connection of some oscillators → series of periodic duplation
- power spectra of electric circuit having nonlinear capacitance



（15）Common feature of self-organization

- many partial systems
- When control condition is changed, the system takes a new type of macro-scale pattern.

［time］
quasi-periodic oscillation, isolated oscillation, many kinds of oscillation, chaos

［space］
honeycomb structure, wave type, spiral type

Self-organization process which comes to a qualitatively new macroscopic structure

1．4 Edge of chaos

Chaos is an important source of novelty and variety in living systems. Critical phase changes in the behavior and structure of complex systems may provide mechanisms by which nature exploits chaos.

[chaos theory]
In mathematics, **chaos theory** describes the behavior of certain dynamical systems– that is, systems whose states evolve with time – that may exhibit dynamics that are highly sensitive to initial conditions (popularly referred to as the butterfly effect). As a result of this sensitivity, which manifests itself as an exponential growth of perturbations in the initial conditions, the behavior of chaotic systems appears to be random. This happens even though these systems are deterministic, meaning that their future dynamics are fully defined by their initial conditions, with no random elements involved, this behavior is known as deterministic chaos, or simply *chaos*.
Chaotic behavior is also observed in natural systems, such as the weather. This may be explained by a chaos-theoretical analysis of a mathematical model of such a system, embodying the laws of physics that are relevant for the natural system.

The **butterfly effect** is a phrase that encapsulates the more technical notion of *sensitive dependence on initial conditions* in chaos theory. Small variations of the initial condition of a dynamical system may produce large variations in the long term behavior of the system. This is sometimes presented as esoteric behavior, but can be exhibited by very simple systems: for example, a ball placed at the crest of a hill might roll into any of several valleys depending on slight differences in initial position. It is a common subject in fiction when presenting scenarios involving time travel and with "what if" scenarios where one storyline diverges at the moment of a seemingly minor event resulting in two significantly different outcomes.

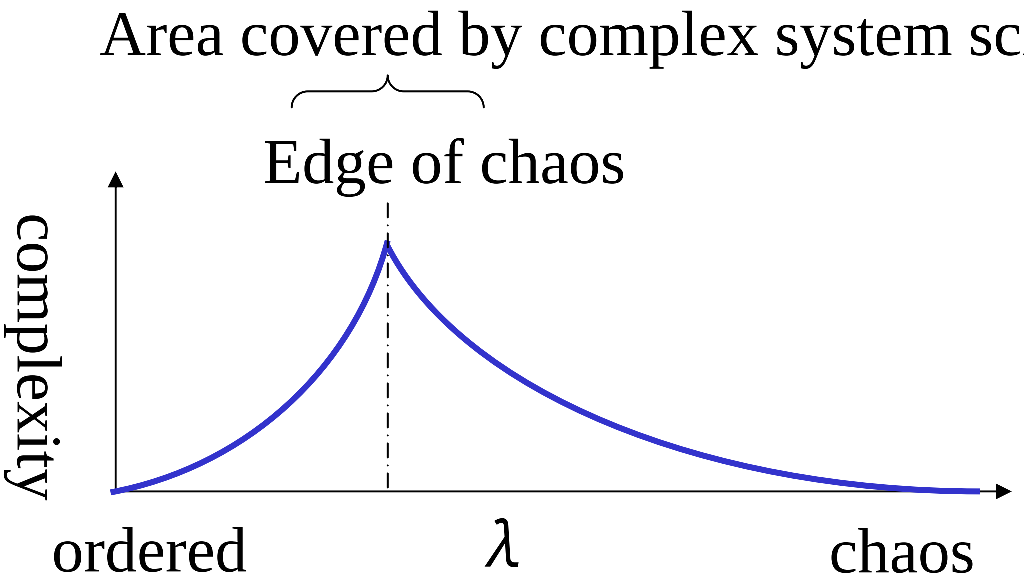
The equations that govern the Lorenz oscillator are:

$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$

where σ is called the Prandtl number and ρ is called the Rayleigh number. All σ, ρ, β > 0, but usually σ = 10, β = 8/3 and ρ is varied. The system exhibits chaotic behavior for ρ = 28 but displays knotted periodic orbits for other values of ρ. For example, with ρ = 99.96 it becomes a *T*(3,2) torus knot.



λ :control parameter
order parameter
（variable which control the behavior）

［edge of chaos］

Kauffman (1992) and Langton (1990, 1992) have suggested as follows.

The ‘edge of chaos’ –the phase change between ordered and chaotic behavior for automata – plays a central role in evolution. Because systems near the edge have the richest, most complex behavior, such systems can adapt better and therefore have a selective advantage over other systems. Therefore living systems have evolved so as to lie close to the edge of chaos. Most of these arguments concern the behavior of automata, and of living things (regarded as automata).

Green (1993, 1994) derives a second theory from observations of phase changes in the structure of complex systems, rather than their behavior.

The transition here is from disconnected to fully connected systems. An important property of this transition is the variability associated with the phase change itself. The transition might be regarded as a ‘chaotic edge’, rather than an ‘edge of chaos’. It is possible that this chaotic edge provides a source of novelty in many natural phenomena (especially in biology). Rather than evolve to sit on the phase change, external stimuli cause the system to flip across it and back. In the connected phase ‘selection’ operates to inhibit variation; in the disconnected phase variation has free reign. It must be discussed how this process may work in real systems. The systems normally exist in the connected phase, for which variation is inhibited.

Life-giving molecules get a scheme of well controlled information processing naturally

Essentiality of life: edge in which a balance is kept desperately

1．5 general description of complex system analysis

（1）object

The mechanism which underlies every complex phenomena and generates the complexity is made clear, and then the theory and technique which controls complex system is established. Consequently fundamental study of complex systems and control and application of complex system are aimed.

（1）Every complex phenomena have some common characteristics

（2）The system is so simple as to be generated due to a model simulated by a computer

What the complex system science studies with is not matter, but procedure and scheme. Then mathematical subject properly acts in connection.

If an abstract model is constituted in a computer and a pattern emerges naturally, it is made an interpretation of complex phenomenon.

The procedure must be understood, and then the subject itself need not be known.

Abstract modeling of subject＋simulation by computer
Analogical interpretation which resolves actual complex phenomena
Complex system science studies methods of approach together.

（2）2 approaches of analyzing complex system science

Approaches of complex system science analysis are divided into 2 main ones.

（1）constitutive method

Complex system is simulated by a computer, and phenomena are interpreted. It is a general method since von Neumann.

（2）phase transition in non-equilibrium and nonlinear problem

Phase transition from order to disorder is treated as bifurcation or stability of non-equilibrium and nonlinear problem.

１．６　Constitutive method

By this method one deepens his understanding of an object as follows.

When one intends to understand an object, he constitutes a fundamental model in a computer, observes its overall behavior and makes change of it.

As far this method has been applied for engineering problem, and now it is applied for understanding natural science. It finds a model to explain the creativity of the nature, and proves the emergency of complexity.

When it applies the complex system science, von Neumann had a conviction “A surfacial complexity comes from a simplicity situated deep down.”

（１）A computer generates a surprisingly complex pattern from a simple mathematical rule.

（２）Surprisingly complex patterns are full of the world.

（３）Complex phenomena can be found by an aid of a computer.

This method is suited for big problem such as origin of life and origin of multi cells being, identifies tactics of artificial life. However, the computer simulation resembles “a game.”

Constitutive method＝「simulation」＋「analogy」

[Constitutive model]

When a subject is not quite understood, a model is constituted by drawing mental picture, and then it is a virtual one. Therefore its validation is carried out by a simulation.

modification of a model ⇒ identification by simulation

[process of identification by simulation]

1. Observation of subject

↓

2. Extraction of features

↓

3. Creation of constitutive model

↓

4. simulation

↓

5. Assessment of results

↓

6. Comparison and consideration between the subject and the constitutive model

[analogy]

positive (similarity)

negative (difference)

neutral

１．７　phase transition in non-equilibrium and nonlinear problem

（１）expression of solution

locus and flow line in space

attractor, nodal point, focal point, limit-cycle, 3 dimensional manifold, strange attractor（chaotic attractor）, bifurcation

（２）bifurcations

①nodal point→nodal point, ②focal point→limit cycle（Hopf bifurcation）,　③limit cycle→limit cycle, ④torus→torus

（３）phase transition in non-equilibrium（fluctuation effect）

（４）growth of spatial pattern

（５）discrete map（Poincare map）, discrete map with noise

（６）self-organization：　control parameter, number of elements, transient phenomenon

（７）nonlinear stochastic differential equation