Our Biologically Inspired Approaches to Advanced Information Technology

Priority Assistance for the Formation of Worldwide Renowned Centers of Research
The 21st Century Center of Excellence Program by MEXT, Japan
Fields of study : Information/Electrics/Electronics

Shojiro NISHIO
Graduate School of Information Science and Technology
Osaka University

PRAGMA 11 Workshop, October 17, 2006

Grad. School of Info. Science and Tech. (IST)

Est. Apr., 2002

Approaching Life Sciences | Bio Information
Dept. of Bioinformatic Eng.

Advanced Content Processing | Multimedia Content
Dept. of Multimedia Eng.

Forming Infrastructures by Advanced IT | Internet
Dept. of Info. Networking

Software | System/Hardware Design
Dept. of Comp. Science | Dept. of Info. Sys. Eng.

Expanding Basic Technologies

Applications of Mathematics | Applied Mathematics and Physics
Dept. of Pure and Applied Math. | Dept. of Info. and Phys. Science

Basic Theories of Information Science

Forming a worldwide IT research center for the 21st century.

Fusion of Life Science and Information Technology (IT)

Applied Info. Sys. Division

Advanced Network Environment Division

IT Research Collaboration Forum OACIS

Est. Jul., 2002

Cybermedia Center (CMC)

Est. Apr., 2000

PRIUS

PRIUS – Fostering of Globally-leading Researchers in Integrated Sciences –

Relation to a Large National Program

The 21st Century Center of Excellence (COE) Program (started in April, 2002)

A program by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan

This program gives priority to supporting the formation of world-class centers of research, and aims to promote the creation of internationally competitive universities that meet the world's highest standards.

- The research group of our graduate school and Cybermedia Center of Osaka University proposed a project under the program title "New Information Technologies for Building a Networked Symbiosis Environment."
- One of the 20 centers in the Information/Electrics/Electronics study area.

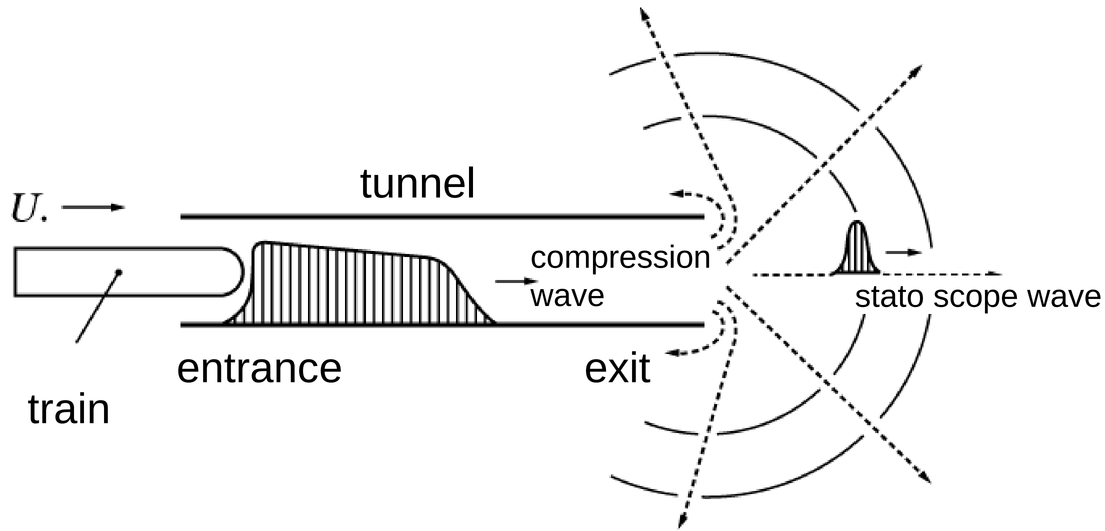
Learning from Living Organisms

Kingsfisher

This beautiful bird is known for its graceful and smooth dive into the water to catch fishes.

Shinkansen (Bullet Train) "500 Series"
(A Recent Model)

Very low noise, which prevents noise pollution.



Projects Adopting Analogies from Bio-Systems

Anthill Project

Bologna Univ.: Exploits the analogy of complex adaptive systems, typically found in biological and social sciences.

BioNet Project

Univ. of California, Irvine + NTT

Autonomous Configuration of Distributed System

University College London

Project eLisa

IBM: Its aim is to drive autonomic capability into current products.

Immunocomputing

International Solvay Institutes for Physics and Chemistry, Belgium

Recovery-Oriented Computing

Univ. of California, Berkeley: A 99.999% failure-free rate is to be achieved.

Structuring Information

Edinburgh Univ.

Systems with Autonomous, Dynamic and Adaptive Components

Univ. of Maryland

Keeping in line with these cases, we focus on symbiosis.

Networked Symbiosis Environment (NSE)

Our Goal

To build a networked symbiosis environment where many humans can live together peacefully supported by highly advanced information technology.

We need some breakthroughs.

The 21st century will be the era of symbiosis.

Our Approach

Developing new biologically inspired approaches, by using the knowledge gained through the analysis of various living organisms' cell behavior.

Based on the Oriental Paradigm

Our development of new IT for the 21st century is based on the oriental symbiosis paradigm, such as the Mahayana Buddhism, which promotes the harmony and co-existence of the various living organisms.

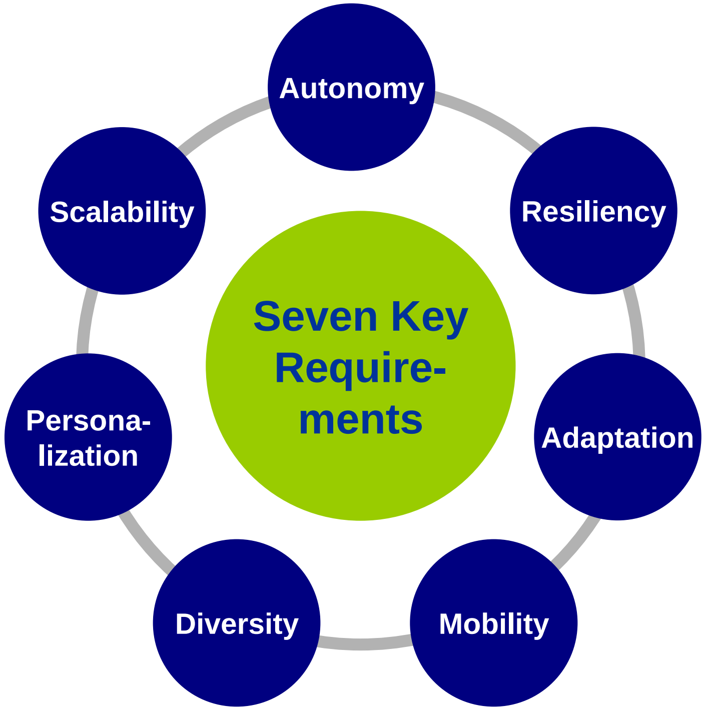
Symbiosis Environment

The environment where each component of the information system selects stable states one after another, and performs its own function, even if any drastic internal as well as external change is given to the component.

The Basic Technologies of NSE and Our Approaches

Symbiotic colony

[Ref: M. Todoroki, et al., BioSystems, 65, 105-112, (2002)]



Networked Symbiosis Environment Architecture

Five research themes

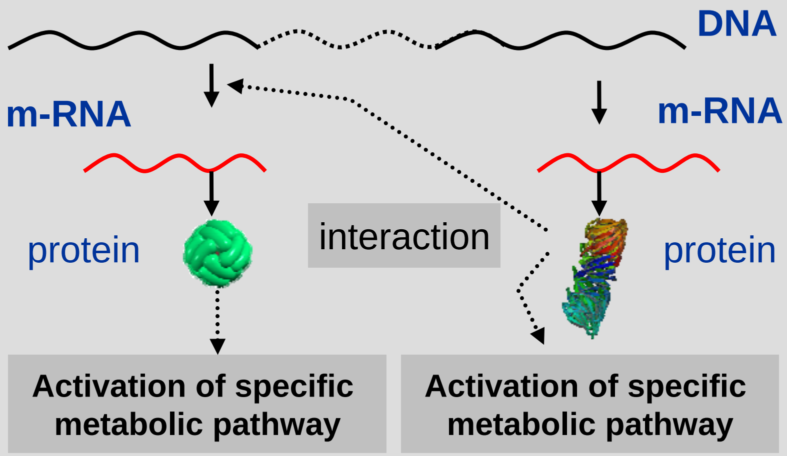
- [Theme 1] Analysis of biological symbiosis network development
- [Theme 2] Establishment of the network architecture for NSE
- [Theme 3] Establishment of community creation mechanism in NSE
- [Theme 4] Technologies for ensuring a reliable and secure NSE
- [Theme 5] Development of symbiosis information systems

Features of our organization

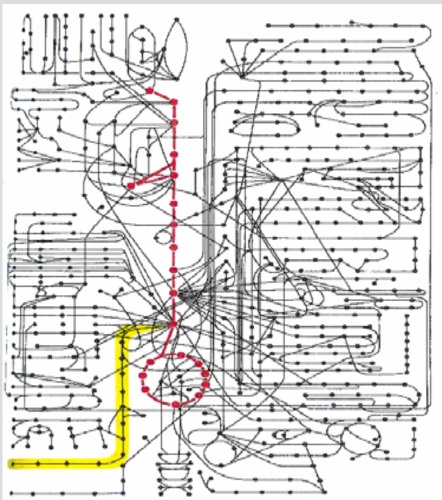
20 members are selected based on:

- Worldwide research activities.
- Giving priority to young researchers.

Bio-Network

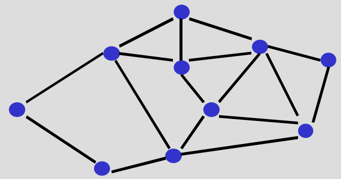


Metabolic Network in Cell



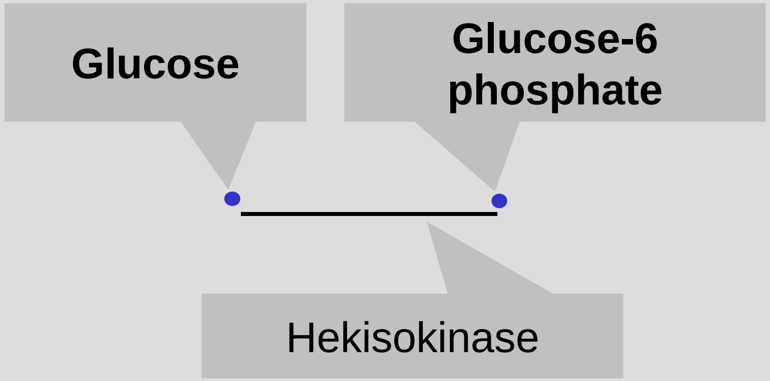
(Molecular Biology of the Cell, 3rd ed.)

Modeling of Metabolic Network



Node：Metabolites
Edge：Metabolic Reactions catalyzed by proteins

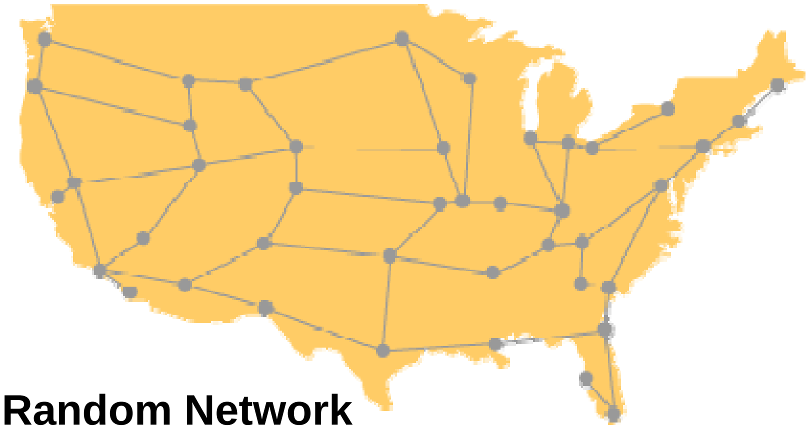
Example (Glycolytic pathway)



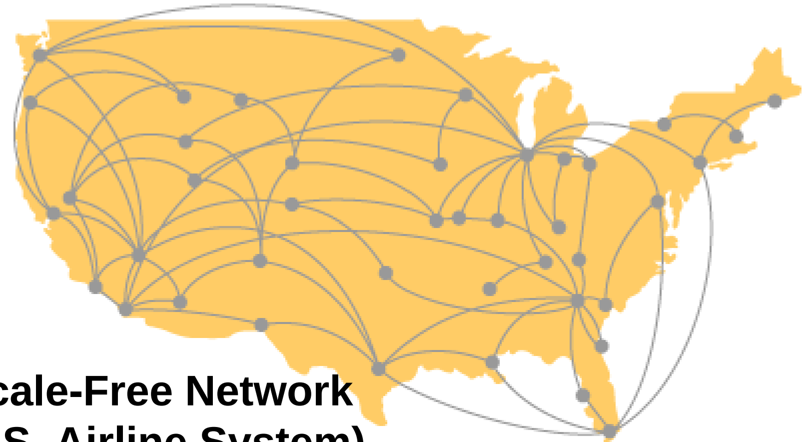
Bio-networks are stable and tolerant to extra-cellar disturbance, because bio-activities derive information, not only locally, but also globally.

Power Law Random vs. Scale-Free Network

Recent Survey!! More than 80% of the Websites had fewer than 4 links, but less than 0.01% of all sites had more than 1,000.

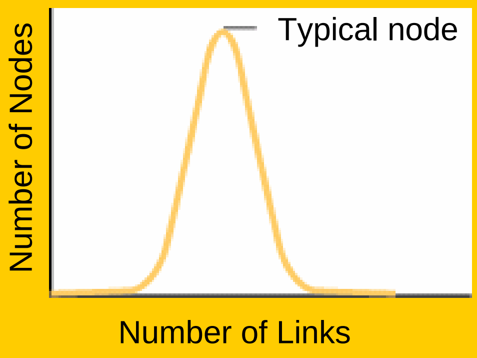


Random Network (U.S. Highway System)

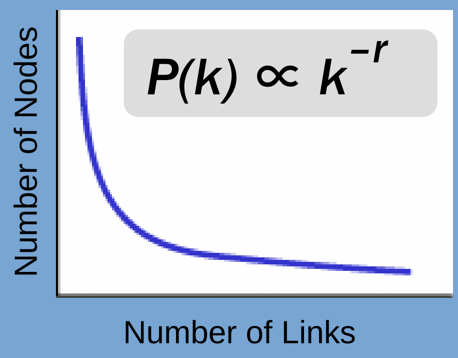


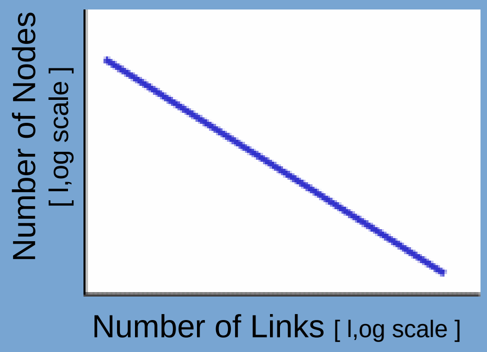
Scale-Free Network (U.S. Airline System)

Bell Curve Distribution of Node Linkages



Power Law Distribution of Node Linkages





Examples: Relationships between "scientists" and "co-authorship of papers", and between "Hollywood actors" and "the appearance in the same movie".

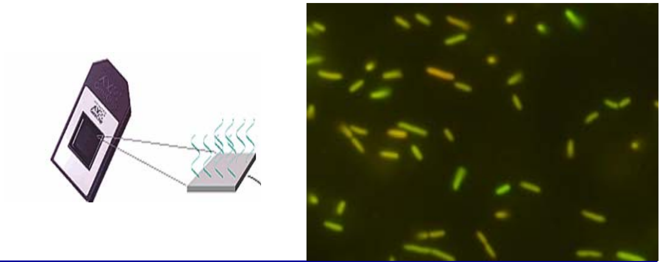
[Result 1] Analysis of Bio- and Information Networks

Objectives

- Finding Common Characteristics in Information and Bio-Networks

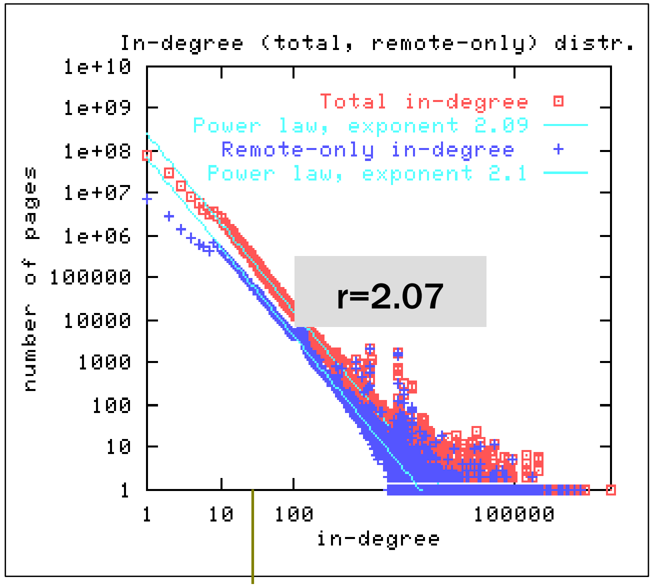
Methods

- Gene Expression Analysis by Gene Chip

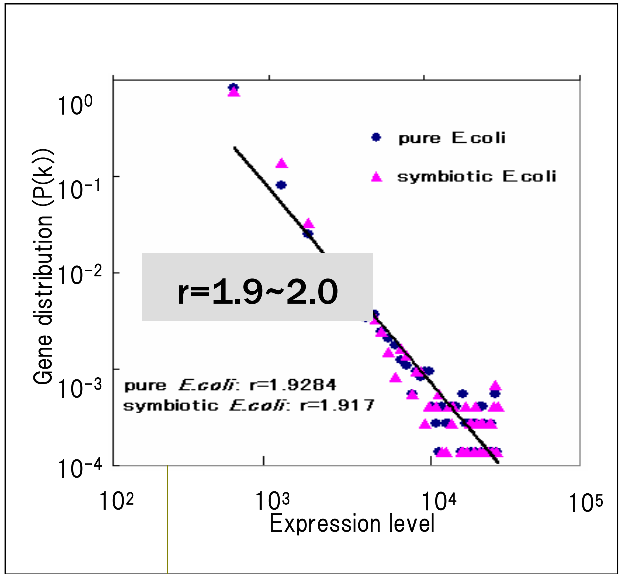


Gene Chip

Distribution Analysis of WWW Site Links



Distribution of Gene Expression of *E.coli*



$$P(k) \propto k^{-r}$$

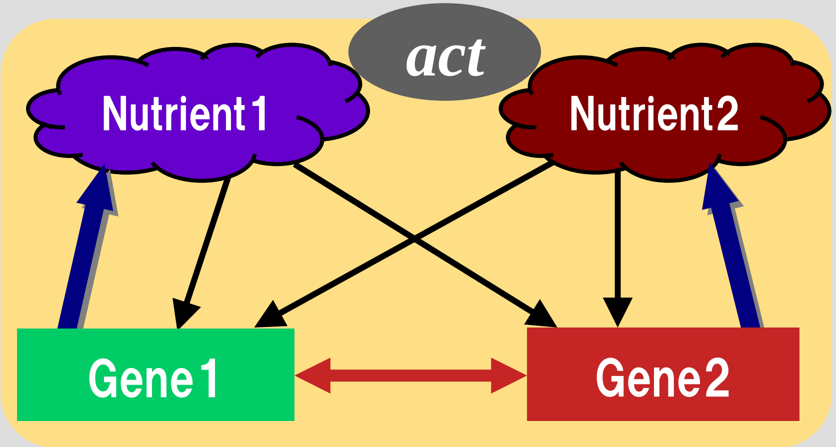
(Power Law)

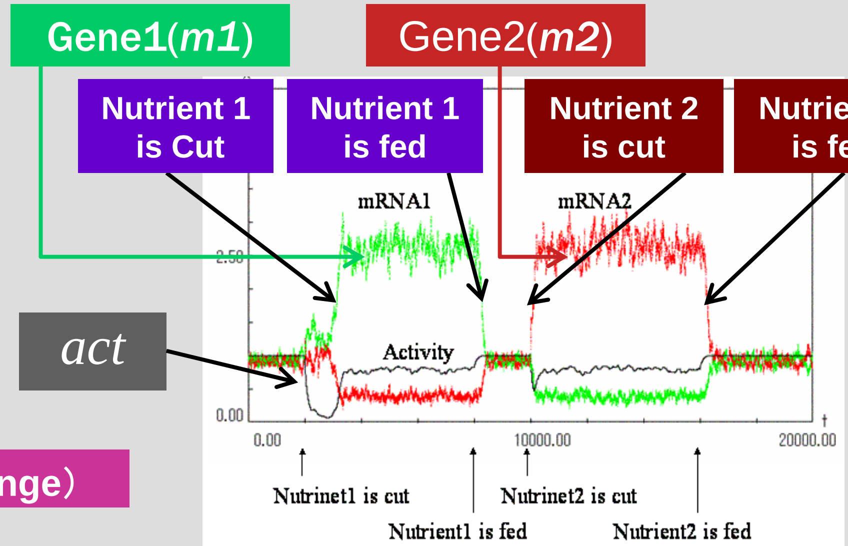
Yomo et al., Them[1]: Proc. Natl. Acad. Sci. , USA, Vol. 100, No. 24, pp. 14086-14090 (Nov. 2003).

X axis: WWW page Links

X axis: Gene Expression (Flow in Metabolic Network)

[Result 2] Adaptive Response of Bio-Networks by Attractor Selection
(Mathematical Representation)





act **(Activity affected by Environmental Change)**

Gene1(*m1*) **Gene2(*m2*)**

$$\frac{d}{dt}m1 = \frac{syn(act)}{1+m2^2} - \deg(act)\times m1 + \eta_1$$

$$\frac{d}{dt}m2 = \frac{syn(act)}{1+m1^2} - \deg(act)\times m2 + \eta_2$$

$$syn\,(act) = \frac{6act}{2+act}, \quad \deg(act) = act$$

White noise independent on System Dynamics

$$\frac{d}{dt}x = f(x)\cdot activity + \eta$$

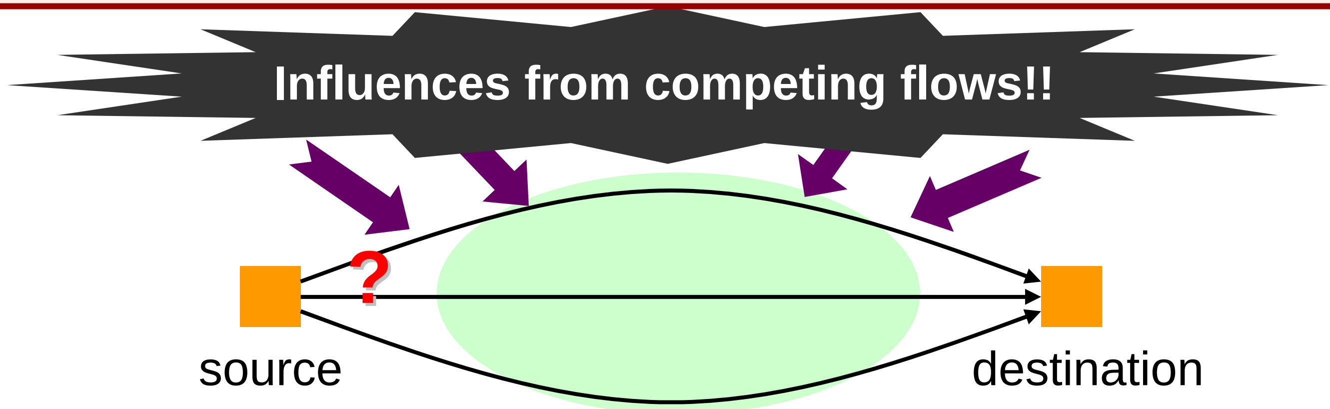
- ***act*** **is changed by environmental conditions.**
- **When act decreases white noise drives systems.**
- **Autonomously a new stable attractor is selected.**

(Attracter Selection of Suitable Gene)

Multi-Path Routing with Attractor Selection (Application of Result 2)

Multi-Path Routing in Overlay Networks

- To obtain application-oriented Quality of Service (QoS), various overlay networks are built on physical IP networks.
- Each source has many paths to the destination and splits its traffic depending on the current condition of the network over each path.



One of the paths is chosen as the primary path over which traffic will be routed with a higher probability. Since their selection strategy is selfish, that is, they only consider to enhance and improve its own QoS, their behavior disrupt each other and the collective performance deteriorates.

- Various unpredictable factors and events change the condition of environment.
- It is very difficult in determining an adaptation rule leading to optimization of the whole system because

Multi-Path Routing with Attractor Selection

ARAS (adaptive response by attractor selection)

- NO RULE adaptation to the dynamically changing environment.
- Everything is implicitly included in the differential equations describing the dynamics of the system.

Chooses the primary path among *M* paths in a probabilistic multi-path routing.

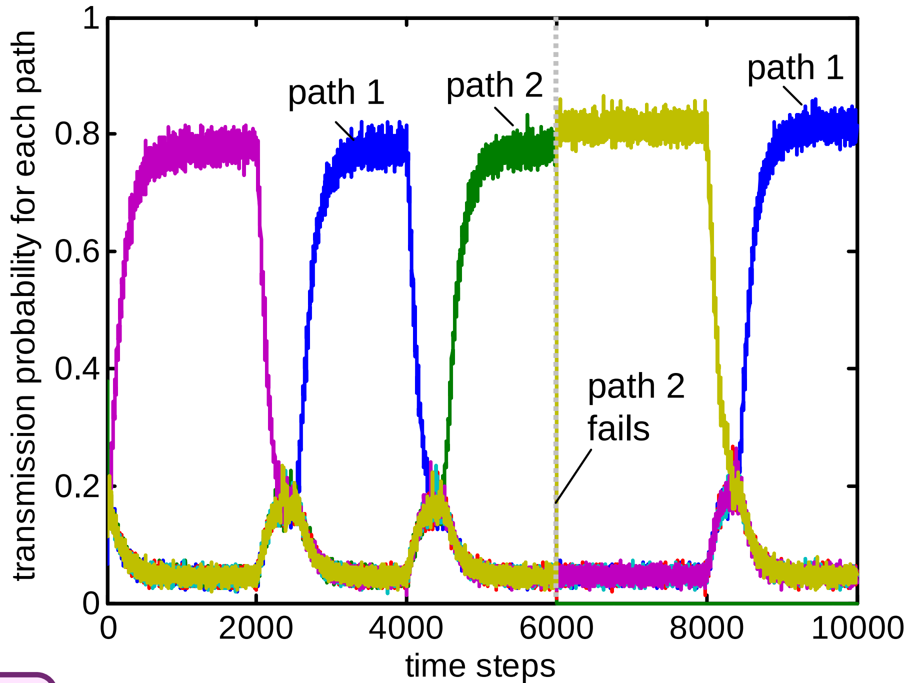
$$\frac{d}{dt}m1 = \frac{syn(act)}{1+m2^2} - \deg(act)\times m1 + \eta_1$$

$$\frac{d}{dt}m2 = \frac{syn(act)}{1+m1^2} - \deg(act)\times m2 + \eta_2$$

Extension of the attractor selection model to an *M*–dimensional model.

$$\frac{dm_i}{dt} = \frac{syn(\alpha)}{1+\overline{m}^2 - m_i^2} - deg(\alpha)\times m_i + (\gamma-\alpha)^{\nu}\eta_i$$

$$\frac{d}{dt}x = f(x)\cdot activity + \eta$$



Kenji Leibnitz et al., Theme[2]: Communications of ACM, March, 2006.

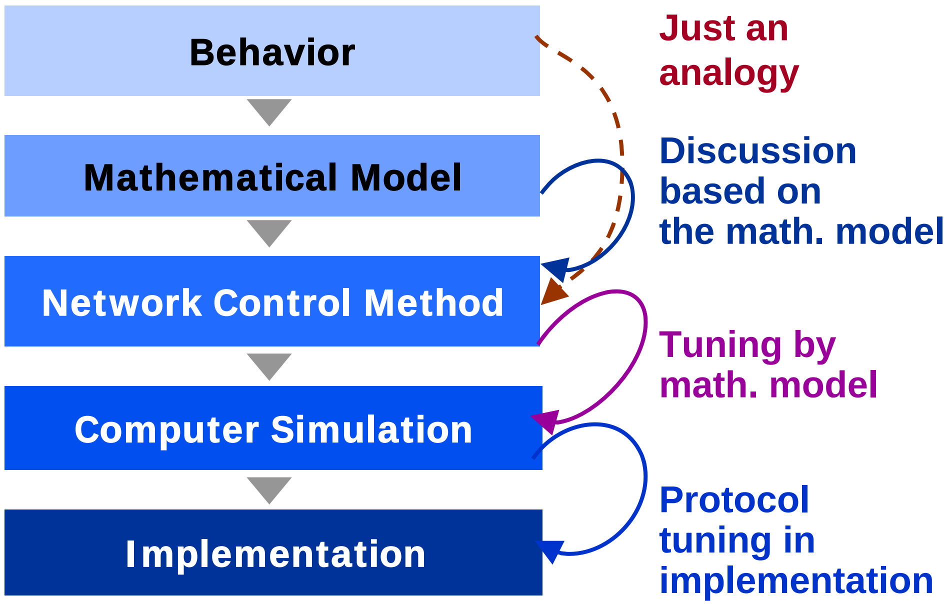
[Result 3] Building of Bio-inspired Network Architectures

- Self-organizing method for data fusion in sensor network based on the synchronization of fireflies. (Pulse-Coupled Oscillator)

- Clustering mechanism for sensor networks. Colonial closure model found in ant behavior.

- Media streaming with cache and resource exploring mechanisms in P2P based of Division of Labor model of bees.

Murata, Wakamiya, and Miyahara:
Results of Theme[2]
presented at **Bio-ADIT 2004**



Important system features:

- Stigmergy
  - Entire system control is achieved by indirect interactions or through environments
- Realizing autonomy, scalability, diversity, mobility, and resiliency

Wireless Sensor Node

A bio-inspired approach to solve the problem of synchronizing wireless sensors for information gathering in an energy-efficient manner.

Applications:

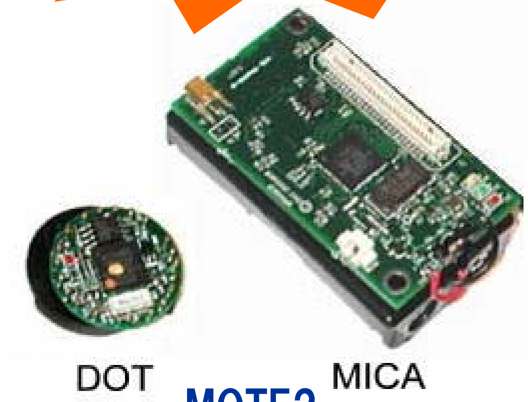
Environmental data sensing:
Gathering the data such as temperature and density of carbon dioxide CO_2.

Intelligent farm:
Gathering periodically the data of temperature, the volume of water in the soil, and other important information.

Sensor node has
- sensors with A/D converters
- general purpose processor
- memory
- radio transceiver
- battery

Sensor node can
- monitor its surroundings
- communicate with each other by broadcasting radio signals

Ubiquitous Computing

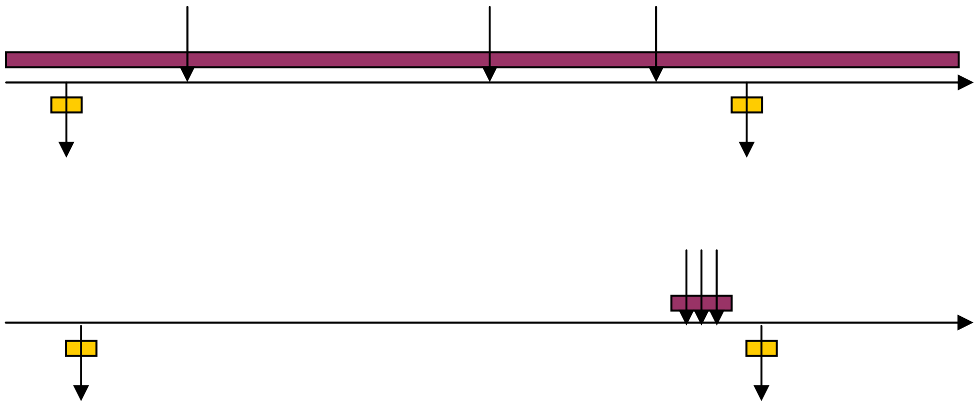


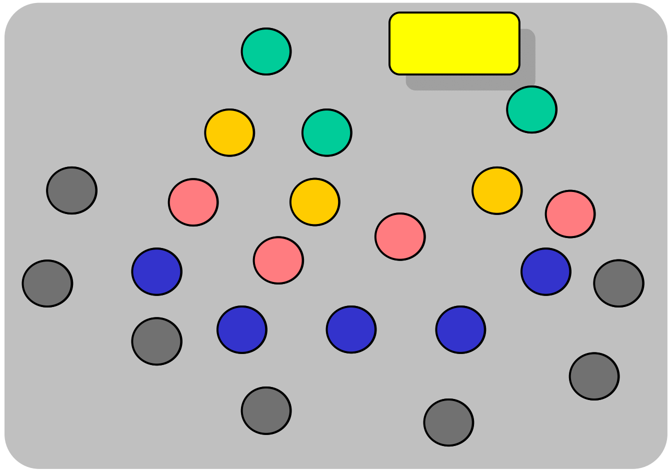
MOTE2
Crossbow Technology, Inc.

Energy-efficient Information Gathering

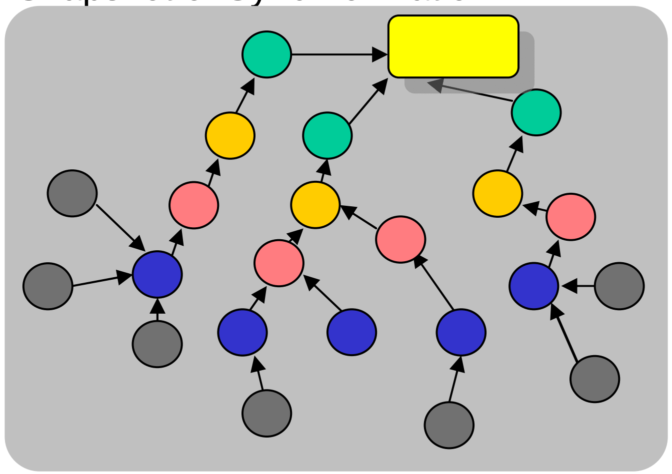
A reasonable way to transfer data from sensor nodes to the base station.

- Collected data periodically propagates from the most distant nodes to a base station.
- Each sensor node integrates its own sensed information and the information received.
- To minimize energy consumption, unused components between data emission are turned off.
- Sensor nodes on the same circumference emit their sensed information in synchronicity and therefore making a concentric circular wave.





Snapshot of Synchronization



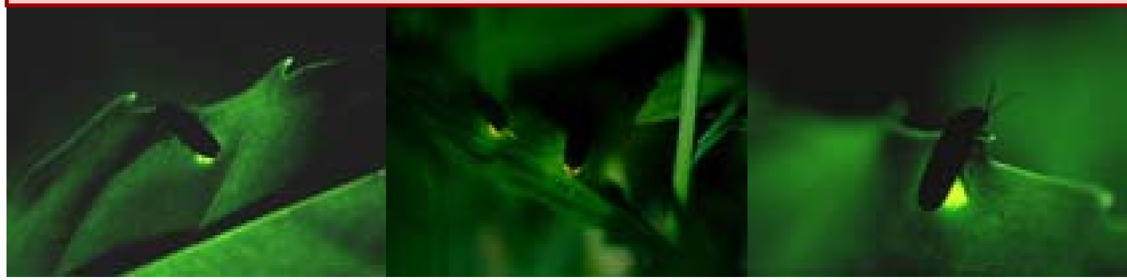
Bio-inspired Approach to Synchronization

System Requirements:

- Each sensor node autonomously determines its timing and frequency of data emission through local interactions.
- Those sensor nodes without direct communications are synchronized when they are on the same circumference.

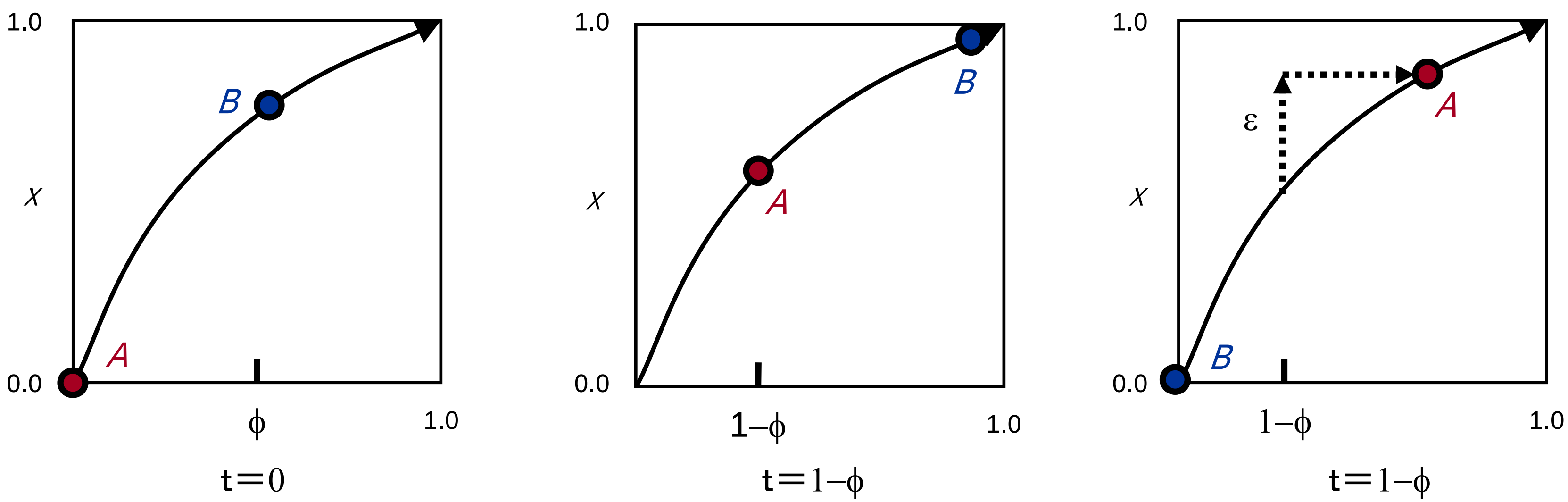
We should learn from fireflies!!

- A group of fireflies in Asia (Pteroptyx Malacae, Pteroptyx Cribellata) can synchronously flash.
  - A firefly flashes independently at its own rate when it is apart from others.
  - When a firefly meets a group, their flashes stimulate it, and this firefly adjusts an internal timer to flash at the same rate as its neighbors.
- The synchronization mechanism is fully-distributed and self-organizing.



Fire Model: Pulse-Coupled Oscillator

- A set of pulse-coupled oscillators $\mathbf{O} = \{O_1, \cdots, O_N\}$
- Each oscillator has a phase ϕ_i and a state $x_i \in [0,1]$
- A phase-state function $x_i = f_i(\phi_i),\ f_i : [0,1] \rightarrow [0,1]$, $i = 1, \cdots, N$
- When x_i reaches 1.0, the oscillator fires.
- Oscillators coupled with O_i are stimulated : $x_i(t) = 1 \Rightarrow x_j(t^+) = \min(1, x_j(t) + \varepsilon)$
- Oscillators O_i and O_j reach synchronization, when O_j also fires.



Contribution to Opening up a New Research Area

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
OSAKA UNIVERSITY

January 29-30, 2004

Lausanne Switzerland

Bio-ADIT 2004

The First International Workshop on Biologically Inspired Approaches to Advanced Information Technology

- Papers are submitted from 25 different countries.
- Acceptance ratio: 28% (Those papers are from 12 different countries.)
- Attendance: 170 (19 different countries),
- Attendance through WWW: 313
- 6 papers of our COE Program are accepted (25% of all accepted papers)
  2 posters are also accepted from our COE Program

Opening up a New Research Area → **Post Conference Proceedings: Springer LNCS, State-of-the-Art Survey Series**

Bio-ADIT 2006

The Second International Workshop on Biologically Inspired Approaches to Advanced Information Technology

January 26-27, 2006, Senri Life Science Center, Osaka, Japan

- Papers are submitted from more than 10 different countries.
- Accepted papers: 22 papers are accepted from more than 50 papers.
- Attendance: 200
- 12 papers of our COE Program are accepted (55% of all accepted papers)
  5 posters are also accepted from our COE Program

→ **Conference Proceedings: Springer LNCS**

Current Status of our Research Program

(We are now in the final year of the five years' program.)

Achievement of our goal :

We have already obtained leading results in the world which realizes the fusion between biology field and information technology by integrating the results of two areas.

Research activities (From 2002, by 20 Program Members) :

More than 343 Journal Papers. More than 553 International Conference Papers. 14 Patents. 48 Research Awards. 122 News Paper Articles.

Very high evaluation at the midterm assessment:

- The top rank score of five grades' evaluation.
- Referred to as one of the programs in the Information/Electrics/Electronics fields which have obtained the most remarkable outcomes in both research and educational activities.

Further Extension of Our Approach (Yuragi Project)

Biosciences

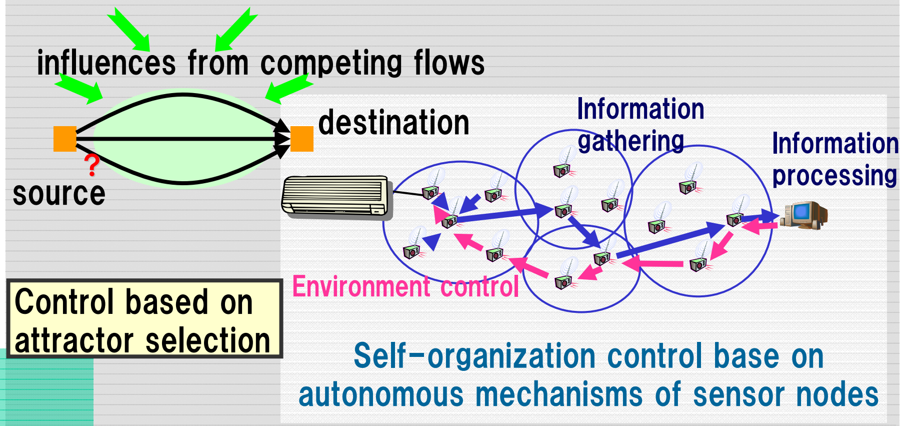
Development of advanced nanobio-imaging techniques to elucidate the mechanisms for fluctuation utilization and attractor selection.

$$\frac{d}{dt}x = f(x)\cdot activity + \eta$$

- Potential with multiple metastable states (multiple attractors) — $f(x)$
- Modulator — $activity$
- Noise — η

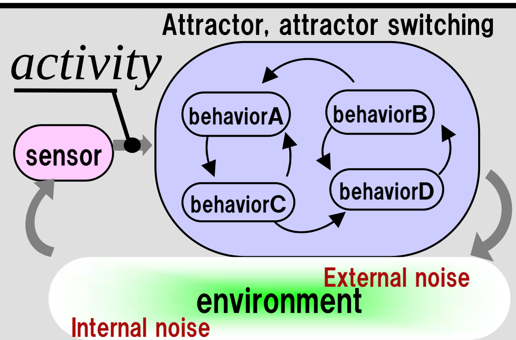
Information Systems

Development of robust information systems based on fluctuation utilization and attractor selection.



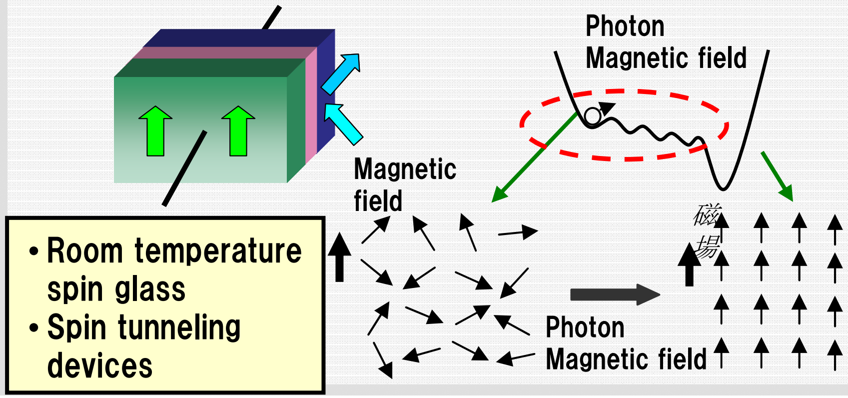
Robotics

Development of control methods based on fluctuation utilization and attractor selection.



Nano・Materials

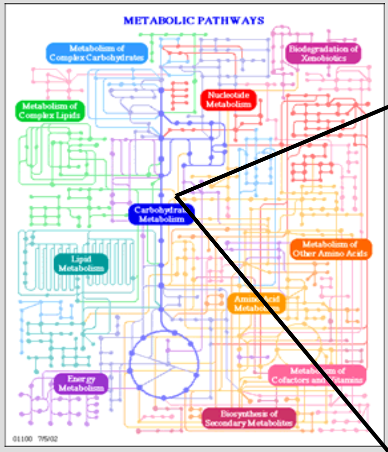
Development of nano-materials realizing fluctuation mechanisms and attractor selection.



- Room temperature spin glass
- Spin tunneling devices

Comparison between Biological and Electronic Systems

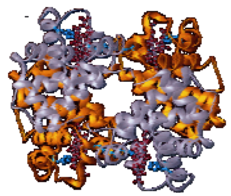
Biological systems



Genetic and metabolic network (KEGG)

Errors of DNA replication process

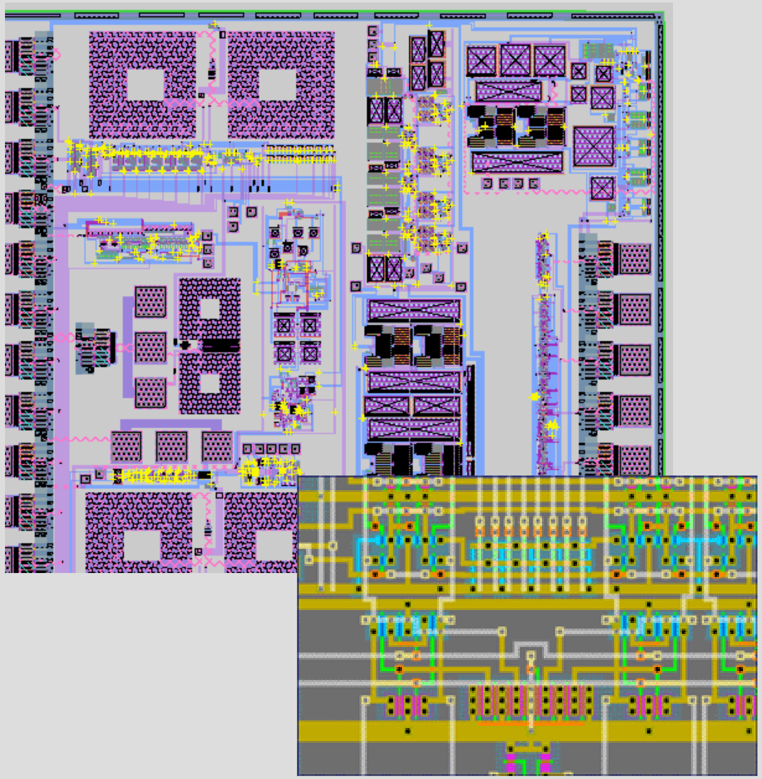
Errors in sequence, conformation, and functions of proteins



...etc

Total error rate is always 1～ 10%.

Electronic systems



No design or operational error is allowed.

Creating a New Paradigm