Thermodynamics-based Strategy to Achieve Balance between Robustness and Performance for Self-organized Network Controls

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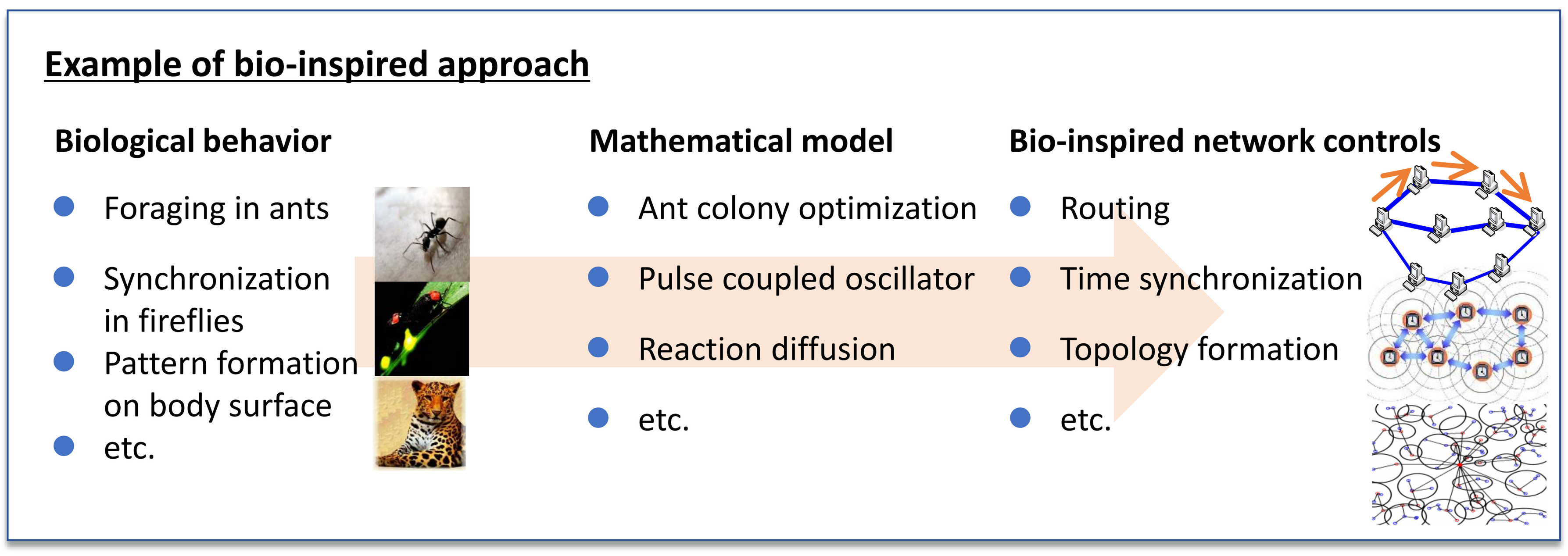
Background and objective of our research

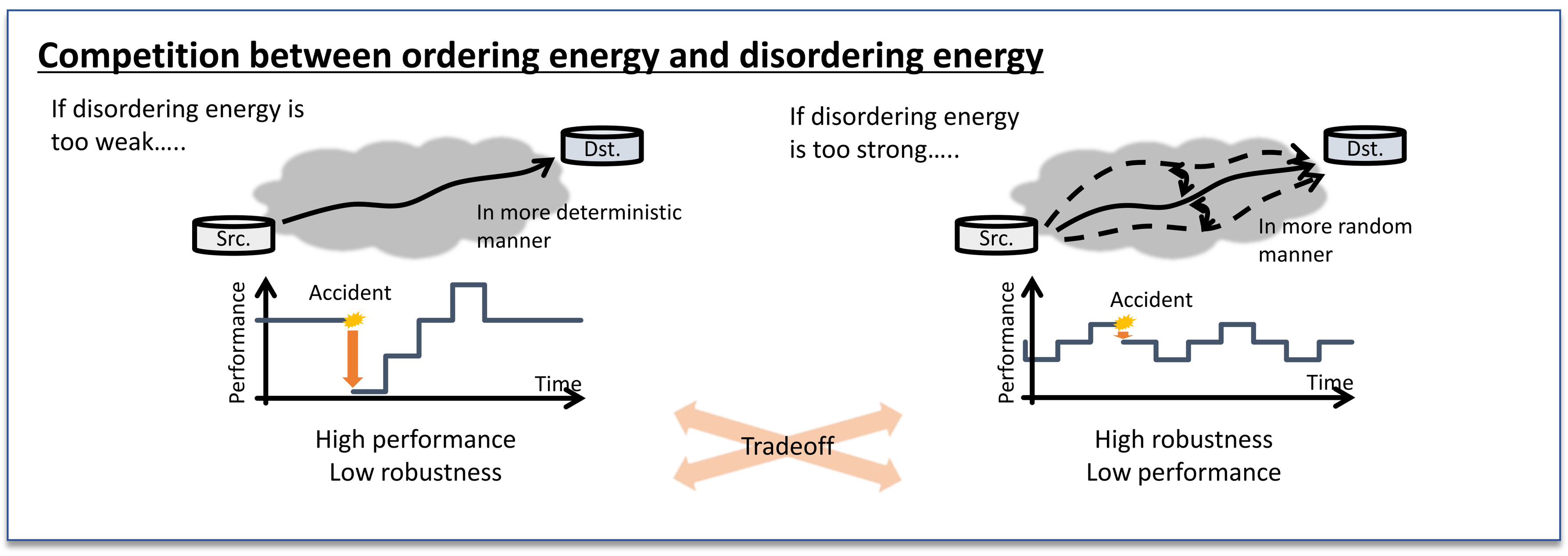
Expectation for biologically inspired network controls

- Information network must be more robust against ever-increasing dynamics & complexity.
- Many researchers are actively working on self-organization-based network controls.
- Many successful attempts published in literatures show their usefulness.



Necessity to equip sufficient robustness with small sacrifice of performance

- In self-organization-based network controls, their useful function, e.g. routing, emerges through competition between their ordering energy[(a)] and disordering energy[(b)].
- Inappropriate balance between both energy leads to insufficient robustness or low performance.



(a) **Ordering energy** makes a network control change its state toward the best state, and this energy makes a significant contribution for achieving high performance.

(b) **Disordering energy** makes a network control change its state veer an unintended state, and this force plays an important role in achieving high robustness, which is a feature to prepare for unexpected failures, e.g. node failures.

We propose a design policy to balance ordering energy with disordering energy depending on the expected degree of environmental fluctuation

Free energy-based design policy for network controls

We analyze the goodness of the balance from the perspective of thermodynamics

- Substance changes its thermodynamic states to achieve the good balance depending on temperature
- Rule of its state change can be explained by

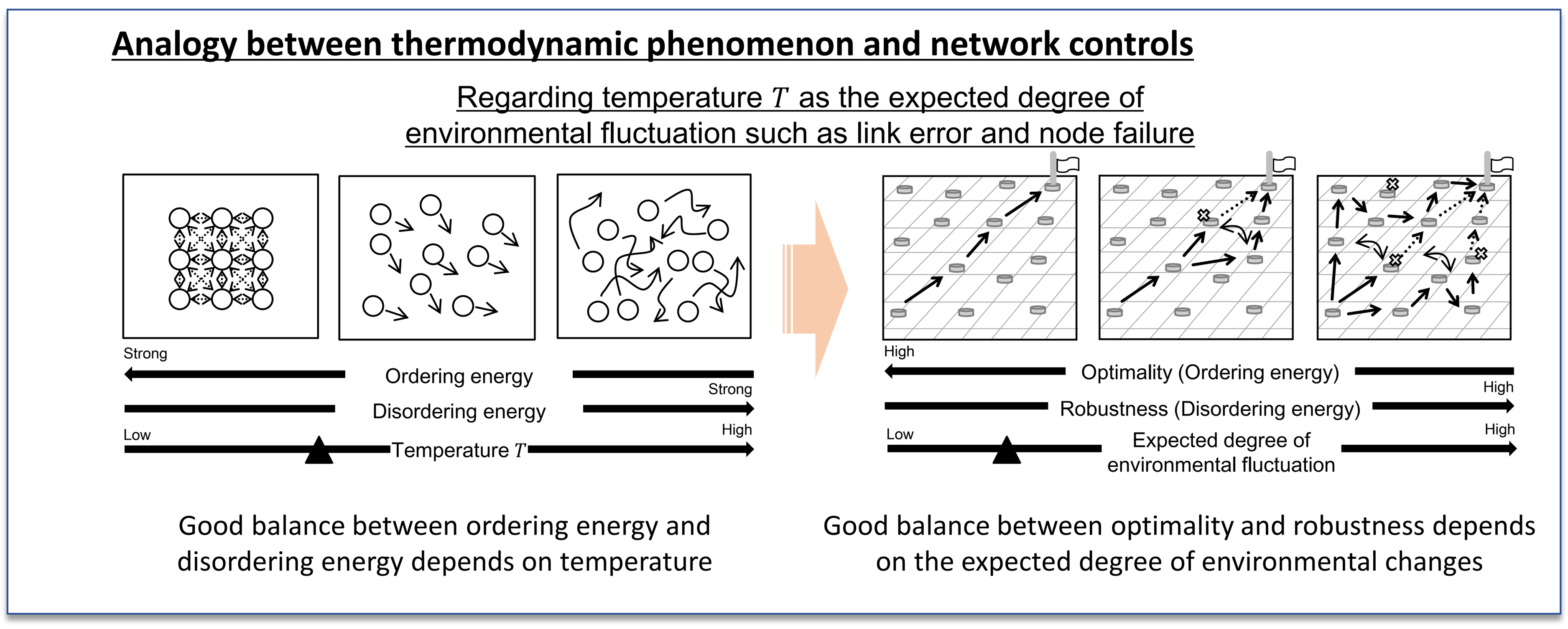
Badness of balance (should be minimized or maximized) — Ordering energy — Disordering energy

$$A = E - T \times S$$

This implies that…

If high temperature T, change of S is effective to change of A
If low temperature T, change of E is effective to change of A

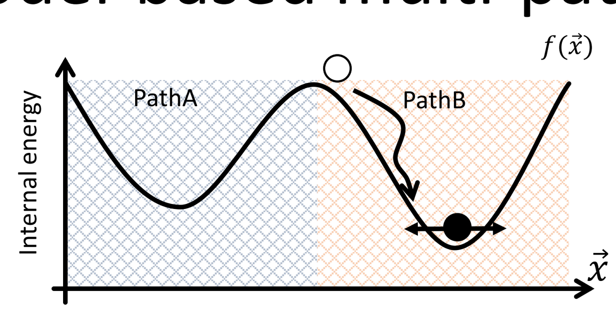
Symbol	Description
Internal energy E	Energy to keep an internal structure of a substance
Entropy S	Randomness of an internal structure of a substance
Temperature T	Parameter to determine balance between E and s
Free energy A	Badness of balance between E and S



Verification of our approach taking a multi-path routing as an example of network controls

- Attractor selection model-based multi-path routing [1]

$$\frac{dx_i}{dt} = \left(\frac{\beta\alpha^{\gamma} + 1/\sqrt{2}}{1 + \max_{1 \le j \le K} x_j^2 - x_i^2} - x_i \right) \times \alpha + \eta_i$$



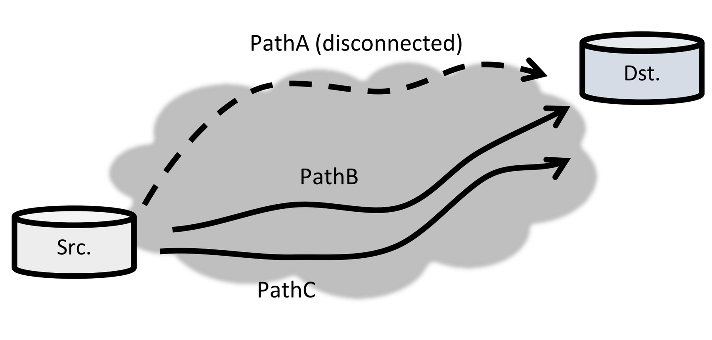
x_i : State, α : Goodness of current path
η_i : Noise, β : Maximum deepness of attractors
$f(\vec{x})$: Potential function

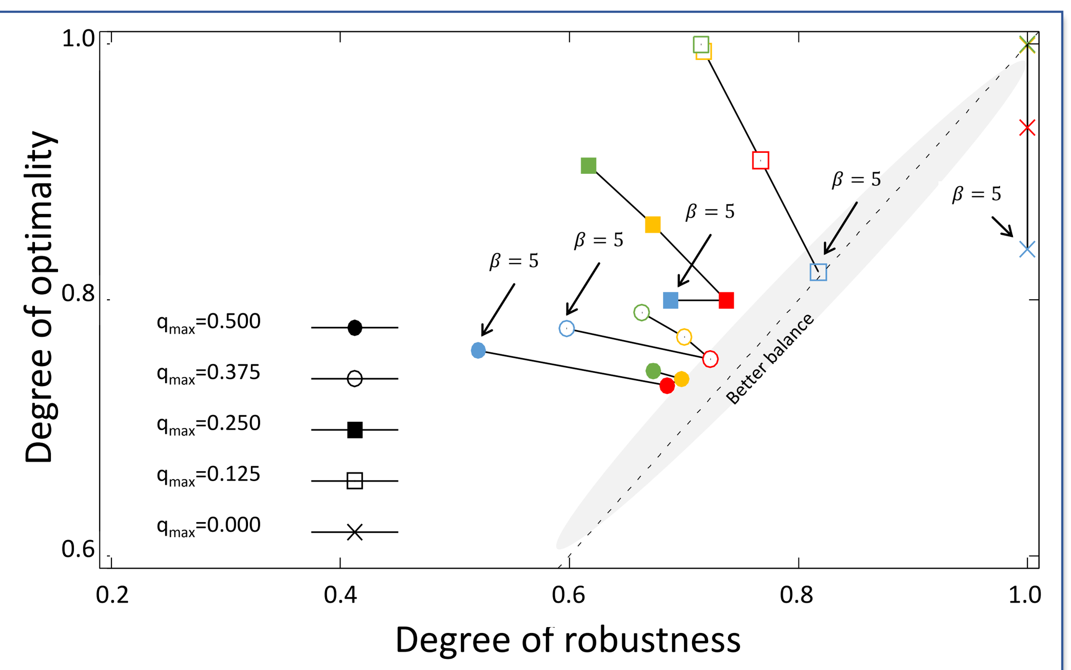
[1] K. Leibnitz, N. Wakamiya, and M. Murata, "Biologically inspired self-adaptive multi-path routing in overlay networks," ACM Communications, vol. 49, pp. 62–67, Mar. 2006.

- Smaller β prioritizes its optimality
- Larger β prioritizes its robustness

Example of simulation result

- 3 node-disjoint paths are constructed
- A source node selects a path using the attractor selection model
- A path is disconnected with probability q_{max} due to environmental fluctuation





The balance between the optimality and the robustness depends on the degree q_{max} of environmental fluctuation