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.

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

\[
 A = E - T \times S
\]

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 \(A\)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>Energy to keep an internal structure of a substance</td>
</tr>
<tr>
<td>(S)</td>
<td>Entropy</td>
</tr>
<tr>
<td>(T)</td>
<td>Temperature</td>
</tr>
<tr>
<td>(A)</td>
<td>Bedness of balance between (E) and (S)</td>
</tr>
</tbody>
</table>

- 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}{dt} = \left( \beta x^2 + x^2 - 1 \right) + a + \eta_t
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\(\eta_t\): Noise
\(\beta\): Maximum deepness of attractors


- Smaller \(\beta\) prioritizes its optimality
- Larger \(\beta\) prioritizes its robustness

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Example of bio-inspired approach

- Biological behavior
  - Foraging in ants
  - Synchronization in fireflies
  - Pattern formation on body surface
  - etc.

- Mathematical model
  - Ant colony optimization
  - Pulse coupled oscillator
  - Reaction diffusion
  - etc.

- Bio-inspired network controls
  - Routing
  - Time synchronization
  - Topology formation
  - etc.

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Example of simulation result

- The balance between the optimality and the robustness depends on the expected degree of environmental fluctuation