

EKC2025 @TU Wien

Memory-aware feedback enhances power in active information engines

 **CHEOL-MIN GHIM**
Physics • Biomedical Engineering
Ulsan National Institute of Science & Technology

UNIST Center for Soft and Living Matter

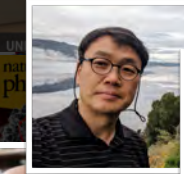
François Amblard
Optics, Soft matter



Hajin Kim
Biomedical imaging



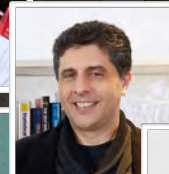
Cheol-Min Ghim
Director, Complex systems, Quantitative biology



Segun Goh (Sejong)
Molecular dynamics



Tsvi Tlusty
Theory of Life



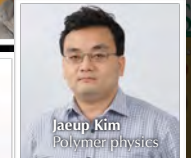
Jae Sung Lee (KIAS)
Stochastic thermodynamics



Chae Un Kim
Protein engineering, crystallography



Robert Mitchell
Microbiology

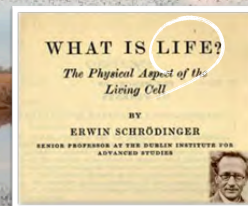


Jaecup Kim
Polymer physics

Joonwoo Jeong
Soft active matter
Neutron scattering

Murmuration of starlings holds the key to the essence of ...

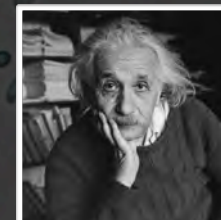
Fundamental physics: universal principles of symmetry breaking and self-organization in nonequilibrium settings across scales



Fluctuations, ... a signature of being alive? [sic]



Robert Brown (1827)



Albert Einstein (1905)

$$m\dot{v} = -\gamma v + \sqrt{2Dk_B T}\xi(t)$$
$$\langle \xi(t) \rangle = 0, \quad \langle \xi_i(t)\xi_j(t') \rangle = \delta_{ij}\delta(t-t')$$
$$D = \mu k_B T$$

“Einstein-Smoluchowski relation”
~ a fluctuation-dissipation theorem

Being alive,
what's special?

- Nonequilibrium steady state
- Struggle against **detailed balance*** through energy dissipation
- Active noise in every scale of life processes: metabolism, allostery, ecology

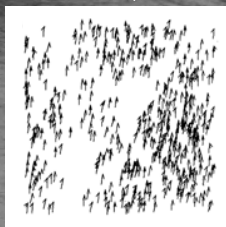
Tamas Vicsek et al., (1995) *Phys. Rev. Lett.*



Disordered gas

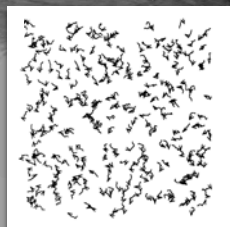
$$\begin{cases} z_k(t+1) = z_k(t) + v_0 e^{i\theta_k(t)} \\ \theta_k(t+1) = \arg \sum_{m \in \mathcal{N}_k(t)} e^{i\theta_m(t)} + \pi \eta \xi_k(t) \end{cases}$$

Microphase separation



Polar liquid

Active Matter Physics



$U(1)$ symmetry breaking \rightarrow 2-dimensional long-range order (Mermin-Wagner violated)

©Xavi Bou

Nonequilibrium is a big deal for...

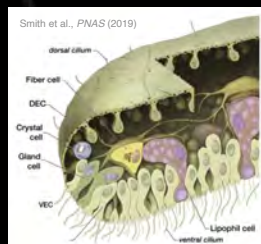
- Long-range order in low-dimensional systems
- Homeostasis: sustained biological steady state
- Chemotaxis: microbial information processing
- Not for free: thermodynamic cost of information

Being alive is **not** about staying **balanced in equilibrium** but about **actively maintaining balance** through **nonequilibrium** processes



Emergence of Non-Neuronal Intelligence

Video credit: Prakash Lab (Stanford)



Trichoplax adhaerens

- Amoeba crawling?
- Directed gliding by coordinated beating of cilia
- Neither neurons nor muscles*

From Fluctuations to Functions: Coordinating Non-neuronal Systems
EMC 2023 @TU Wien

7

Chemotaxis of earlier multicellular organisms?

- C, H, O, N, etc.
- > Macromolecules
- > (Autocatalysis/Replication) > Single-celled organism
- > **(Emergence of intelligence) > Multicellular organism**
- > (Nervous system) > "Higher" organisms



WORLD ECONOMIC FORUM

EMERGING TECHNOLOGIES

Your brain has more in common with an ant colony than you realised

Jan 10, 2019 Deborah M. Gordon (Biology, Stanford)

This article was originally published by **Big Think.**

Swarm Intelligence in Microbial Systems

Emergence of collective learning, adaptation, and decision-making from local interactions among multiple decentralized agents—natural or artificial

↳ Tackling problems no single agent could solve alone

Feherman group (Weizmann), PNAS 2024

Colloidal Heat Engine: a Microscopic Stirling Engine

A microscopic single-bath heat engine, comprising a single colloidal particle subject to a time-dependent optical trap

• Blickle & Bechinger, *Nat. Phys.* **8**, 143 (2012)
 • Roy et al., *Nat. Comm.* **12**, 4927 (2021)
 • Krishnamurthy et al., *Nat. Phys.* **12**, 1134 (2016)

Szilard Engine: From Undergraduate Lecture Note

A gas particle in a box

• Work extracted from a single heat bath:

$$W = \int_{V_0}^{2V_0} p dV = k_B T \int_{V_0}^{2V_0} \frac{dV}{V} = k_B T \ln 2$$

... thanks to the reduced entropy of Universe!

$$\Delta H = \overline{H(X|M)} - H(X) = -H(M) = -\ln 2$$

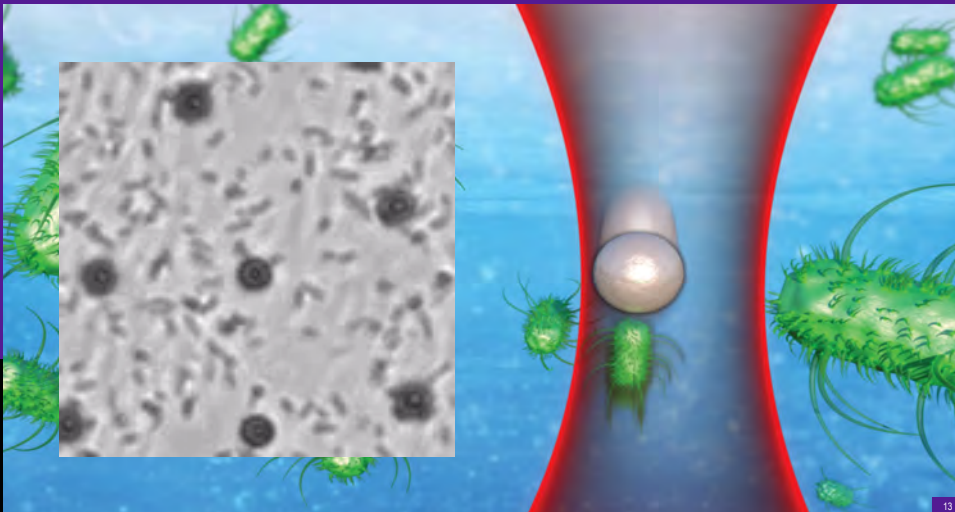
$$\Rightarrow \Delta S_{\text{tot}} = -k_B \ln 2 \Rightarrow W_{\text{ext}} = k_B T \ln 2$$

• How to save the 2nd law?

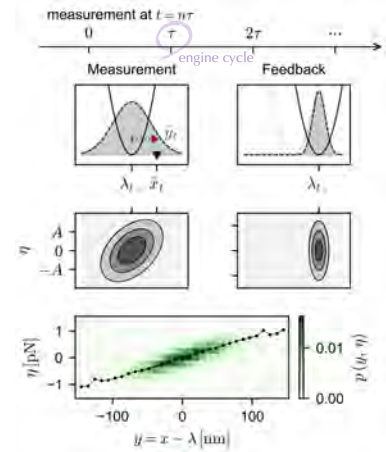
***Landauer's principle:** $Q_{\text{erasure}} \geq k_B T \ln 2$
 Erasure of one bit of information must be accompanied by at least $k_B T \ln 2$ heat dissipation (+external work).

Computation is inevitably done with real physical degrees of freedom, obeying the laws of physics.
"Information is Physical"

Information Engine Operating in an Active Reservoir



Information Engine: Bringing Maxwell's Demon in a Single Bath



SH Bahng, JS Lee, & CMG, <http://arxiv.org/abs/2508.16866>

- EOM for a Brownian particle in active bath

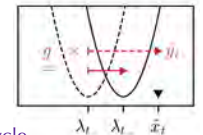
$$\gamma \dot{x}_t = -\kappa(x_t - \lambda_t) + \xi_t + \eta_t$$

$$\langle \xi_t \rangle = 0, \quad \langle \xi_t \xi_{t'} \rangle = 2\gamma k_B T \delta(t - t')$$

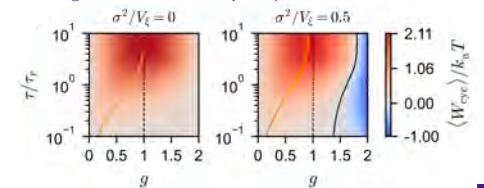
$$\langle \eta_t \rangle = 0, \quad \langle \eta_t \eta_{t'} \rangle = A^2 \exp(-|t' - t|/\tau_c)$$

"Active Ornstein-Uhlenbeck Process (AOUP)"

- Key challenge: Memory-preserving feedback: Abrupt resetting disrupts bath-particle memory



- Average work extraction per cycle



Summary

- UNIST Center for Soft and Living Matter
- A modern perspective on "What is Life?" through the lens of NESM
- NESM perspectives on "Fluctuations to Functions"
 - Active matter
 - Emergence of intelligence
 - Biological information processing
 - Design principles for high-performance information engine
 - Swarm intelligence in distributive systems



Collaboration wanted, and we mean it!
cmghim@unist.ac.kr

Research Goals: Emergence of Intelligence

- Emergence of Intelligence
 - Observation, reconstruction and control of swarm intelligence in microbial systems
 - Understanding swarm intelligence as a form of collective behavior of active matter

- Pushing the boundaries to cover intelligent active matter
- Developing control principles by swarm intelligence

Proc. Nat. Acad. Sci. USA
Vol. 71, No. 10, pp. 4133-4139, October 1974

Kinetic Proofreading: A New Mechanism for Reducing Errors in Biosynthetic Processes Requiring High Specificity
(protein synthesis/DNA replication/amino-acid recognition)

J. J. HOPFIELD

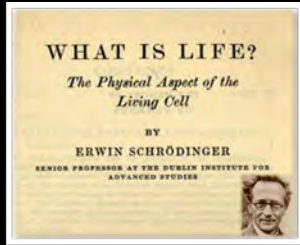
Department of Physics, Princeton University, Princeton, New Jersey 08540; and Bell Laboratories, Murray Hill, New Jersey 07974

Contributed by John J. Hopfield, August 6, 1974

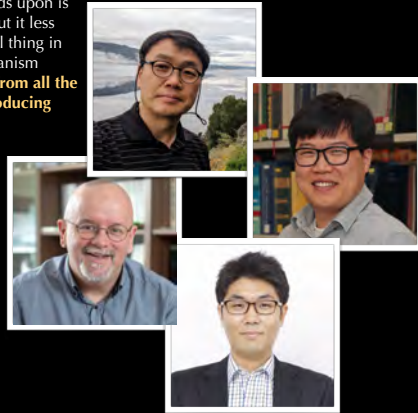
ABSTRACT The specificity with which the genetic code is read in protein synthesis, and with which other highly specific biosynthetic reactions take place, can be increased above the level available from free energy differences in intermediates or kinetic barriers by a process defined here as kinetic proofreading. A simple kinetic pathway is described which results in this proofreading when the reaction is strongly but nonspecifically driven, e.g., by phosphate hydrolysis. Protein synthesis, amino acid recognition, and DNA replication, all exhibit the features of this model. In each case, known reactions which otherwise appear to be useless or deleterious complications are seen to be essential to the proofreading

action path, it is possible to reduce the fraction of substantially below exp $-(\Delta G_{\text{cat}}/RT)$. From a philosophical point of view, if it were possible to proofread the set (or the site recognition during synthesis) since we some precision as the conventional first identifiable fraction of errors would drop to [exp $-(\Delta G_{\text{cat}}/RT)]^2$, such proofreading is conceptually possible, there is no mechanism for such proofreading in the recognition of protein synthesis. Proofreading or "editing" has been noted in DNA replication (5, 6), but a detailed description of its chemical kinetic basis is lacking. The problem is

A Big Question: Emergence of Intelligence



Erwin Schrödinger (1944)
 "... What an organism feeds upon is **negative entropy**. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in **freeing itself from all the entropy it cannot help producing while alive ...**"

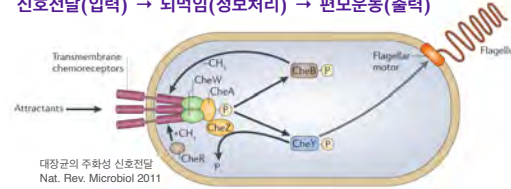


"Fantastic Four" (2025)

- What Schrödinger only hinted at, but never fully unpacked, was the **thermodynamics of systems far from equilibrium**.
- If we really want a solid, quantitative, physics-based understanding of life, the first step is the study of **nonequilibrium statistical mechanics (NESM) in active matter**.
- A goldmine at the x-roads of information theory and NESM: emergence of intelligence. Let's dive into swarm intelligence —how it showed up even before nervous systems evolved!

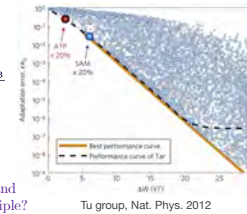
[1] Information Thermodynamics of Chemotaxis

- 세포 수준 정보처리의 전형: 정보엔진으로서의 주화성 신호전달(입력) → 되먹임(정보처리) → 편모운동(출력)



- Maxwell's demon으로서의 생물학적 되먹임의 정보열역학

(1) 다양한 되먹임회로에서 열역학적 불확정성원리 $\frac{\langle(\Delta J)^2\rangle}{\langle J\rangle^2} \geq \frac{2k_B}{S}$ 발굴 및 검증

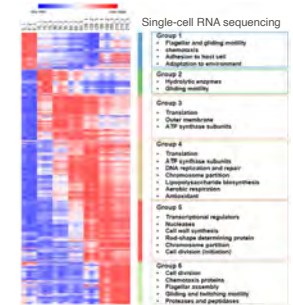


(2) 농도구배 정보의 획득과 관련된 자유에너지 흠출점

Optimal trade-off between sensing accuracy and thermodynamic cost, as per Landauer's principle?

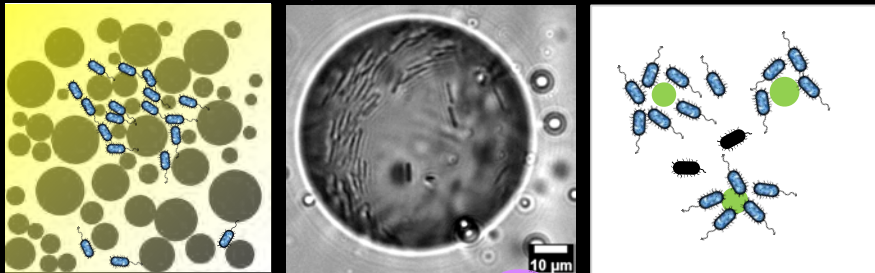
- 적응에 따른 되먹임의 강도 변화 (*Bdellovibrio* 포식활동에 대한 선행연구 지속)

- (1) 단일세포 RNA sequencing: 유전자 발현의 변화를 실험적으로 규명
- (2) 게임이론, 합성생태학 모형 수립/분석



[2] Swarm Intelligence in Complex Environments (Microbial Version of Ant Experiment)

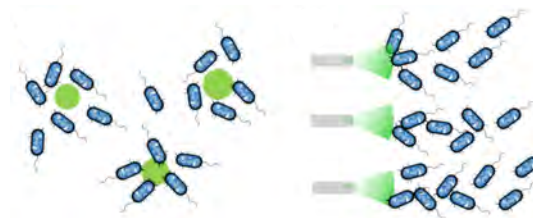
- 미생물 떼지능을 관찰/테스트할 복잡한 환경의 구현
 실험실에서 관찰 가능한, 자연을 모사하는 떼지능 발현환경 설계/구축
 Projects: 흐름이 있는 다공성 물질 구현; 영양분/산소/자원 분포의 실험적 모사



- 복잡한 환경에서 떼지능의 창발에 따른 자기조직화-자기최적화 관찰
 생존 관련 떼지능 테스트 및 관찰; 상호작용을 기반으로 한 떼지능 창발의 이해
 Projects: 잡음이 많은 환경에서의 집단소통, 한정된 자원의 효율적 분배문제, 집단메모리 형성과 전송

[연구2: 계속] 게임의 떼지능 vs. 미생물의 떼지능

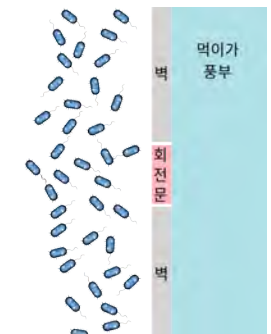
- 제한된 자원소비의 최적화
- 공급 패턴 조절: <매표소 줄서기> 문제



- 돌니바퀴가 열리면 먹이가 나오는 환경에서 미생물들은 돌니바퀴를 열 수 있을까? 혹은 그렇게 진화할 것인가?



- 박테리아들이 회전문을 열고 먹이가 풍부한 곳으로 이동할 수 있을까?

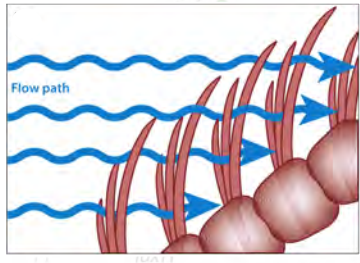


[연구3] 정족수 감지 Quorum sensing를 통한 떼지능의 유도

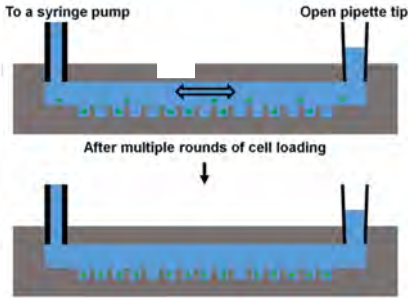


Ghim, BMB Reports 2011

- 유체 환경에서 자가유도물질의 수송(communication)
 - ⇒ 유체역학적 시뮬레이션을 통해 확산을 포함한 실제적인 수송과정을 규명
- 미생물 사이의 커뮤니케이션이 미생물의 표현형에 미치는 영향
 - ⇒ 마이크로웰 실험에서 자가유도물질 농도를 인위적으로 조절하며 집단거동 변화 관찰



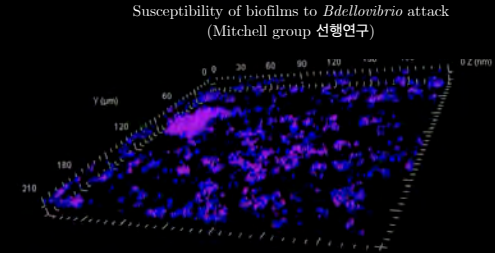
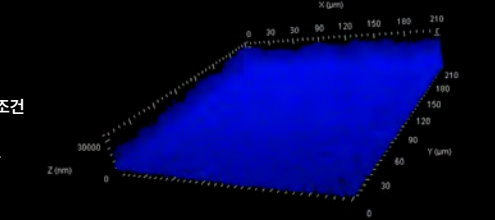
총류/확산/난류를 통한 신호전달분자의 이동
Annu. Rev. Fluid Mech. 41, 73 (2009)



Microwell 실험 모식도. Sci. Rep. 6, 33883 (2016)

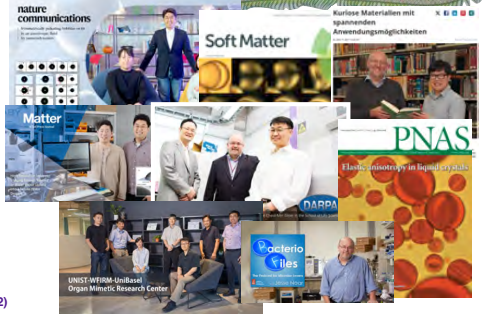
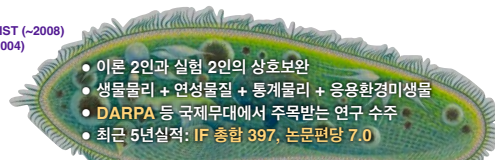
[연구4] 포식자-피식자 시스템에서의 떼지능: Synthetic Ecology

- 포식 박테리아의 상호작용과 포식효율
 - ▷ *Bdellovibrio*의 포식동역학
 - ▷ *M. xanthus*의 집단수렴(foraging) 전략 평가
- 피식 박테리아의 집단방어전략
 - ▷ 통제된 합성생태적 환경에서 바이오필름의 형성/붕괴 조건
- 최적화 문제
 - ▷ 피식균의 농도에 따른 *Bdellovibrio* 포식활동 변화
 - ▷ 군집의 크기가 적응과정을 통해 조절되는 기작 규명
 - ▷ 게임이론 + Vicsek 모형 (선행연구)



"Fantastic Four"

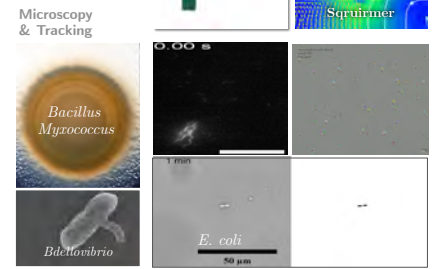
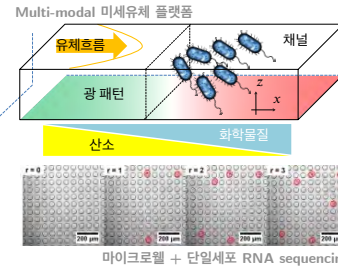
- UNIST (2009-)
- Postdoc: LLNL, CCNY, UCSD (~2009)
- PhD in Physics, SNU (2003)
- UNIST (2008-)
- Postdoc: Harvard Medical, KIST (~2008)
- PhD in Microbiology, GIST (2004)



- Sejong University (2025-)
- Postdoc: Dusseldorf, Jülich, KIAS (~2025)
- PhD in Physics, SNU (2020)
- UNIST (2015-)
- Postdoc: UPenn (~2014)
- PhD in Physics, KAIST (2012)

Our Experimental · Analytical · AI Platforms (1)

- 미생물을 다양한 외부 자극 환경에 놓고 관찰할 수 있는 실험 플랫폼 구비
 - ▷ 미생물 친화적인 미세구조의 공정 유경험
 - ▷ 떼지능 유발/관찰/제어를 위하여 빛, 산소, 화학물질 등 다양한 외부자극 동시인가
 - ▷ 연구에 최적화된 다양한 미생물주 보유, 유전자 편집 가능
- 확률열역학/정보열역학/유체역학 이론 및 수치해석
 - ▷ 비평형통계 및 정보엔진 관련 연구 수행 중
 - ▷ 대규모 유체역학 시스템 전산시뮬레이션



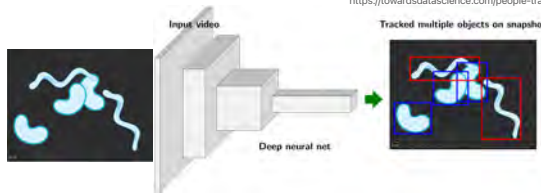
Our Experimental · Analytical · AI Platforms (2)

● AI 활용 미생물 군집거동 해석 (Preliminary)

- ▷ 박테리아 운동, 분열 등 대용량 데이터를 획득하고 분석하는 AI 파이프라인 구축
- ▷ 딥러닝 기반의 객체추적: Kalman filter, Decision tree, Support vector machine 등의 통계적 접근법
- ▷ SORT, GOTURN, MDNet 등 딥러닝 기반의 알고리즘을 활용하여 객체추적 정확도 향상
- ▷ 분류된 개체들의 시계열 영상으로부터 활동특이성, 집단거동 등을 학습하고 딥러닝으로 해석



Pedestrian tracking through Deep Sort
<https://towardsdatascience.com/people-tracking-using-deep-learning-5c90d43774be>



미생물 군집
동적 거동의 정밀추적