How do you explore without a brain?

Readings for today

- Reid, C. R., Latty, T., Dussutour, A., & Beekman, M. (2012). Slime mold uses an externalized spatial “memory” to navigate in complex environments. Proceedings of the National Academy of Sciences, 109(43), 17490-17494.

- Huo, H., He, R., Zhang, R., & Yuan, J. (2021). Swimming Escherichia coli Cells Explore the Environment by Lévy Walk. Applied and Environmental Microbiology, 87(6), e02429-20.

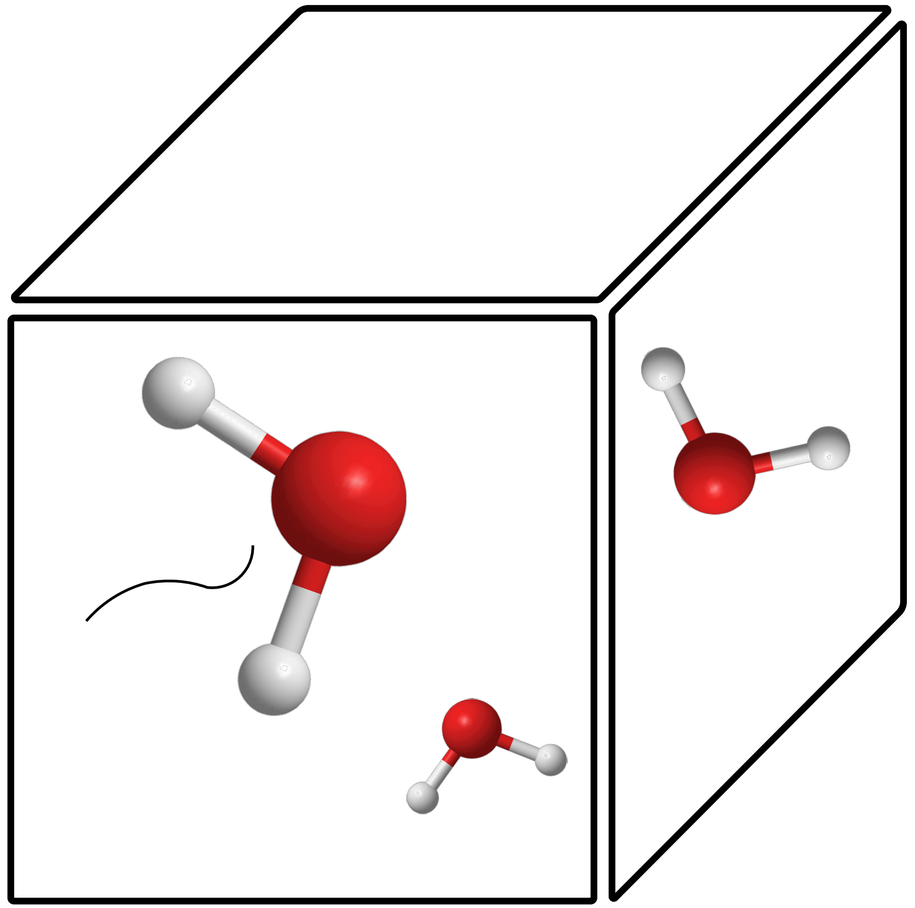
Topics

- Simple forms of exploration
- Organisms that explore without brains

Simple forms of exploration

What is the optimal way to explore?

An optimal exploration policy is one that samples every option at least once.



Brownian motion

In 1D space

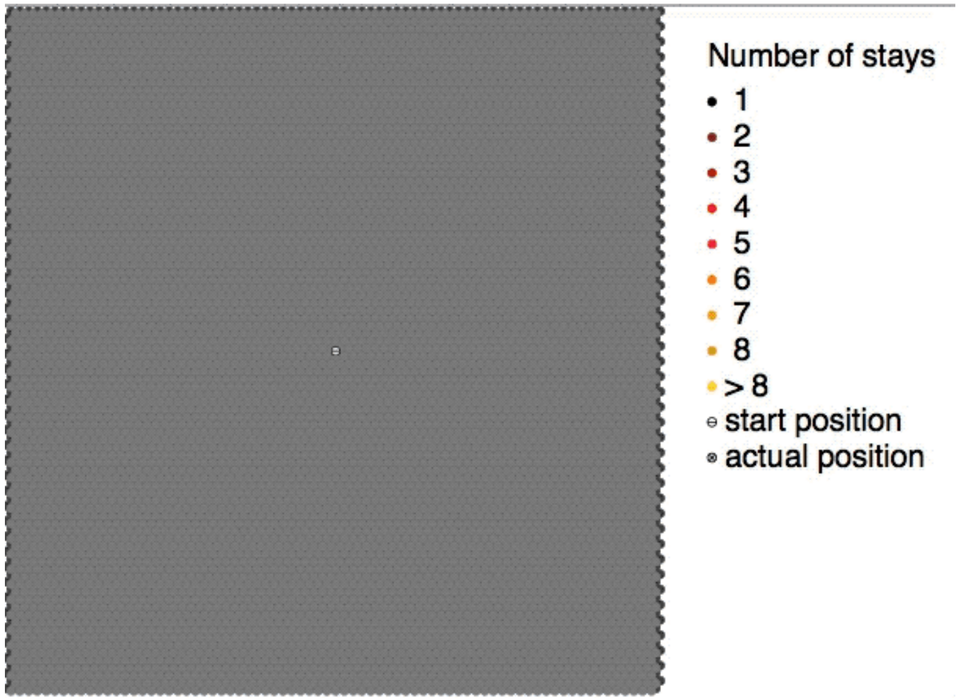
$$x_i = x_{i-1} + u_i, \quad u_i \sim N(\mu, \sigma)$$

In 2D space

$$\theta_i = v_i 2\pi, \quad v_i \sim U(-\pi, \pi)$$

$$x_i = x_{i-1} + u_i \cos(\theta_i)$$

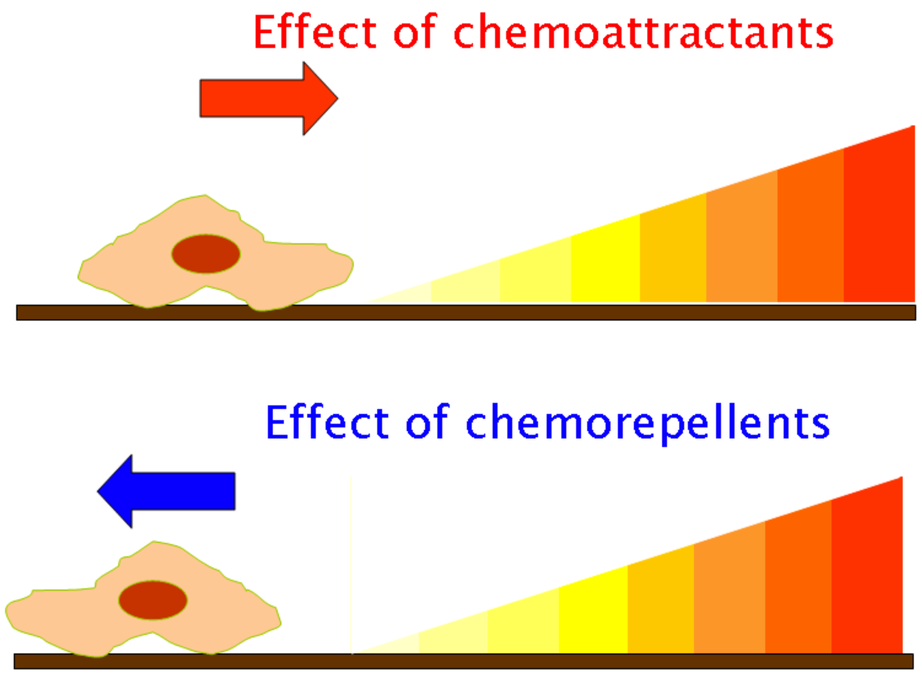
$$y_i = y_{i-1} + u_i \sin(\theta_i)$$

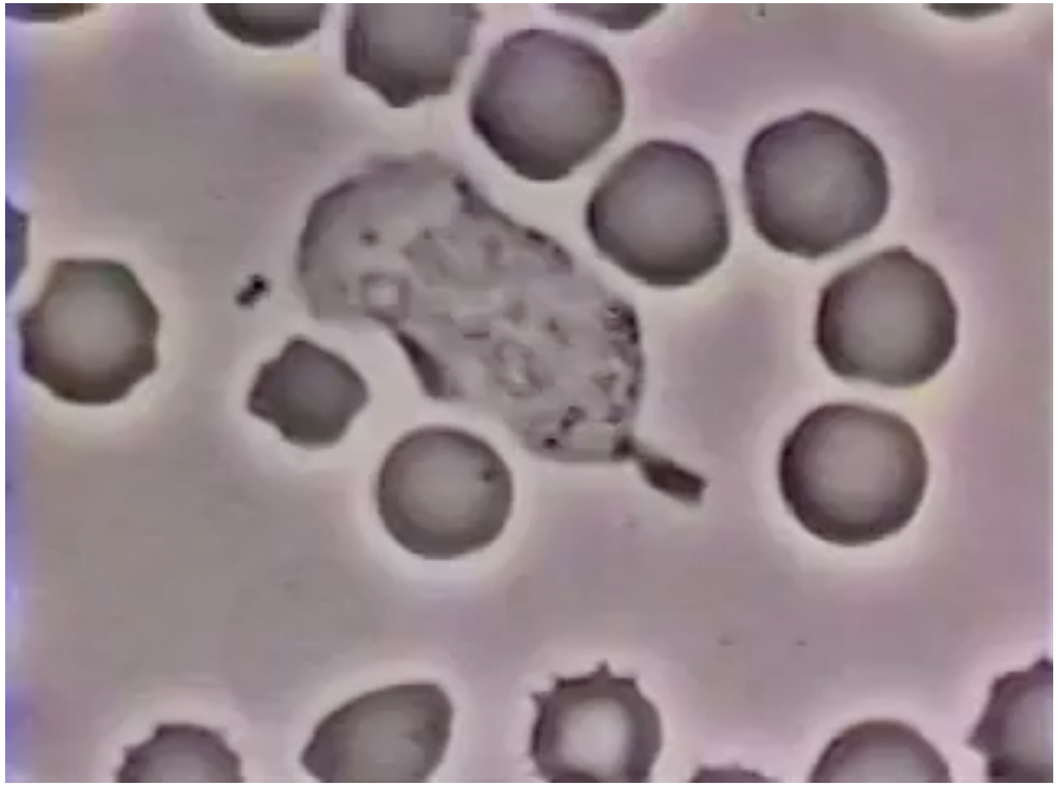


2D random walk of a silver adaptor on a Ag(111) surface (source: Wikipedia; Marburg et al. 2017)

Chemotaxis

Movement in response to a chemical stimulus.

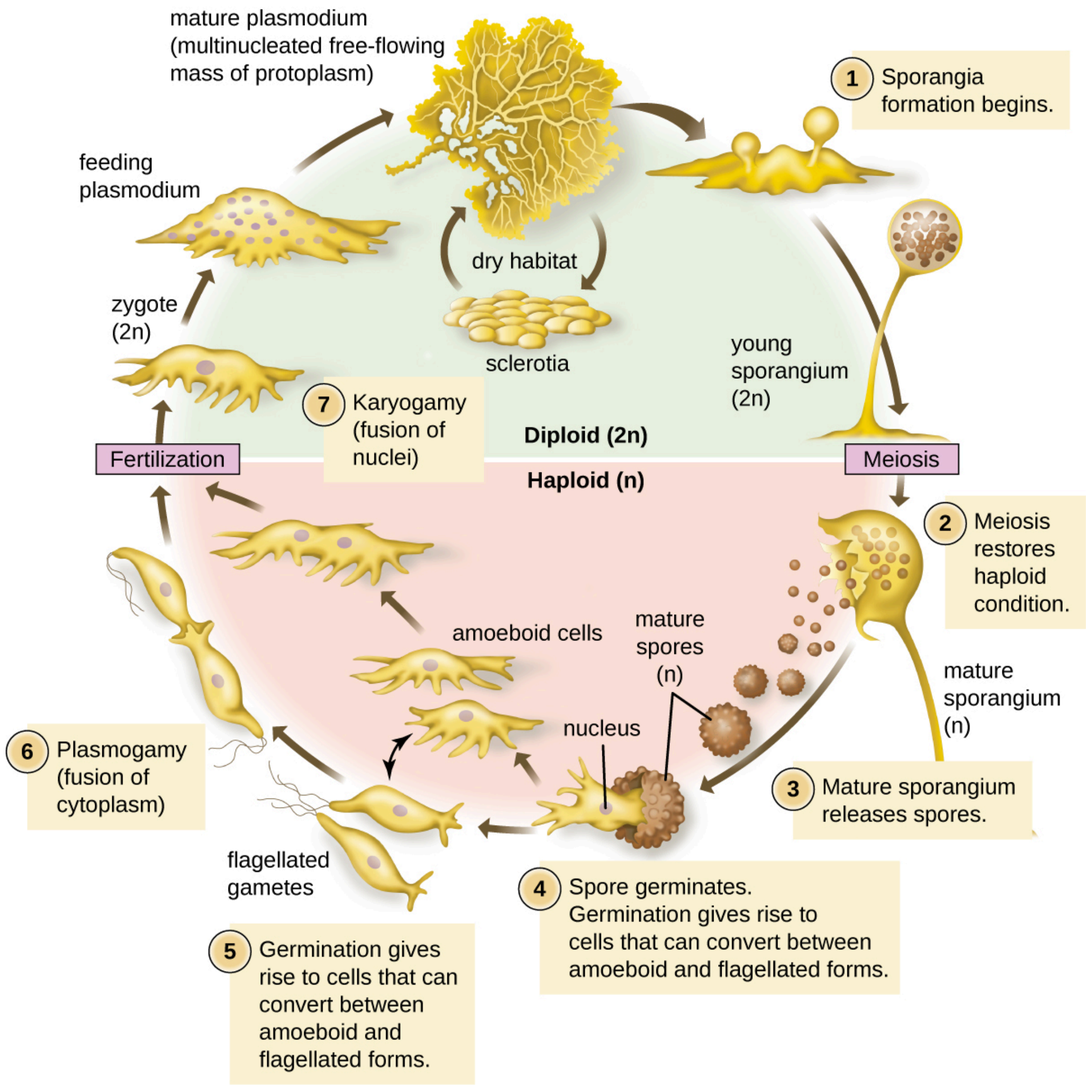




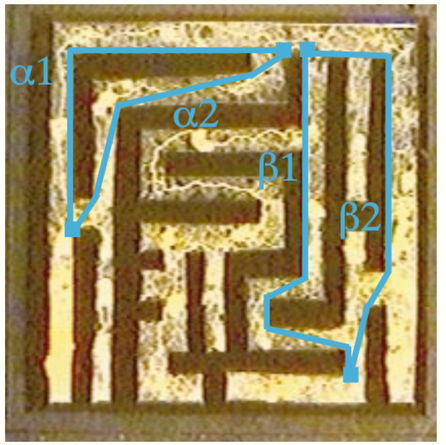
https://routledgetextbooks.com/textbooks/9780815344506/videos.php

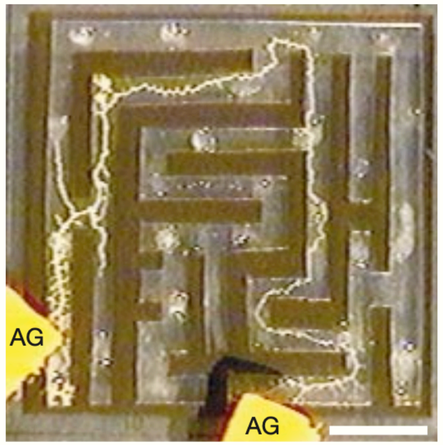
Organisms that explore without a brain

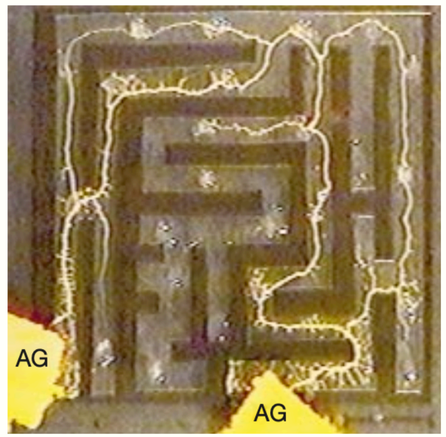
Organism 1: slime mold



Slime mold navigation







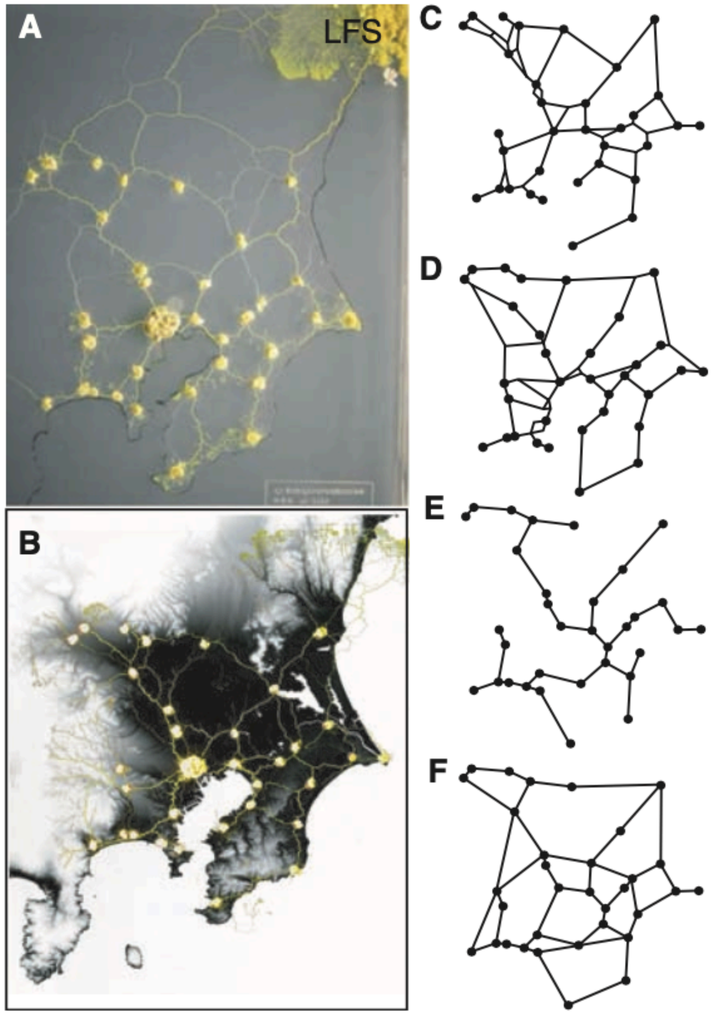
d

	None	β1	β2	β1, β2
None	2	0	0	0
α1	0	0	0	0
α2	0	5	6	3
α1, α2	0	0	0	3

Slime molds can find optimal foraging routes through nutrients (and obstacles)

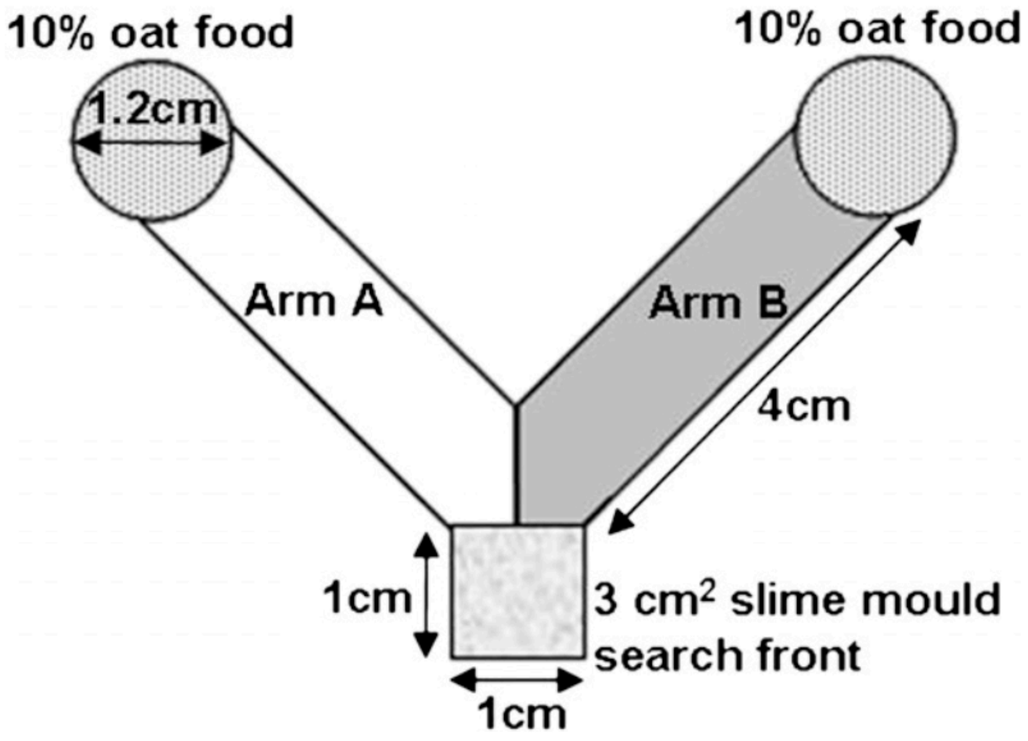
(Nagaki et al. 2000)

Path minimization



(Tero et al. 2010)

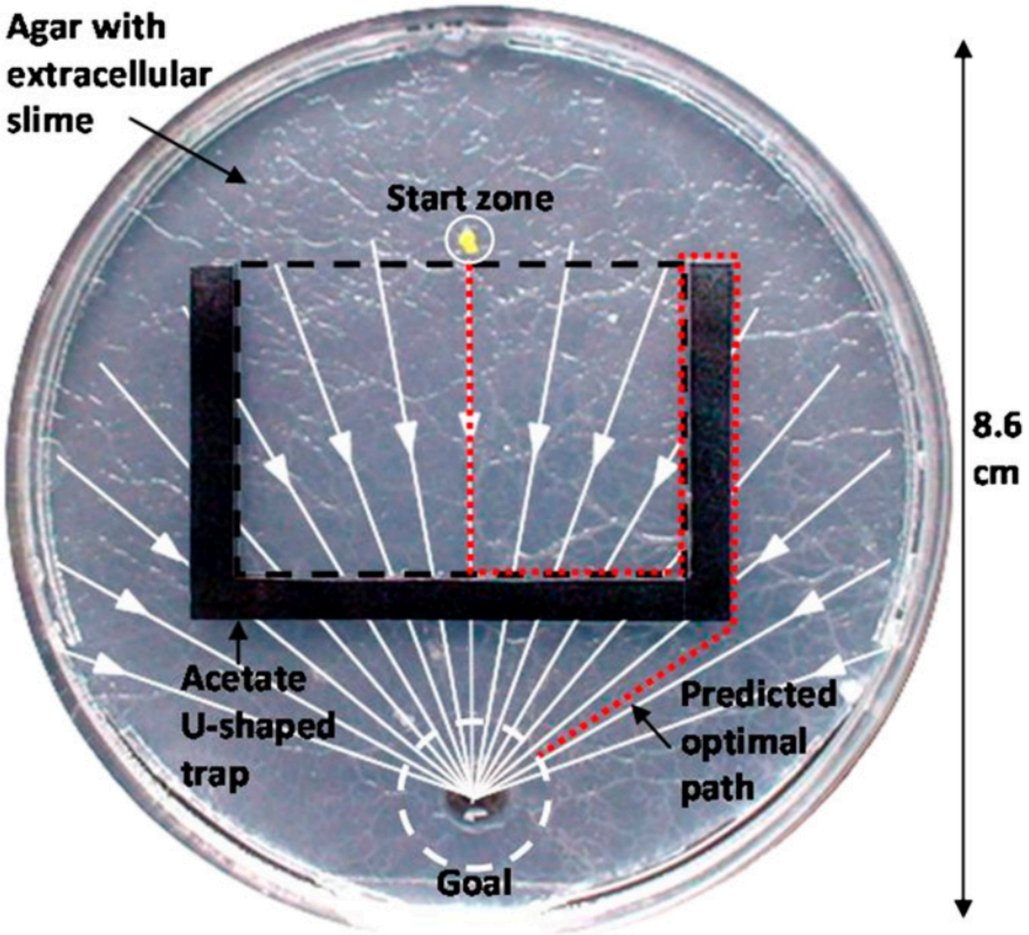
Making choices

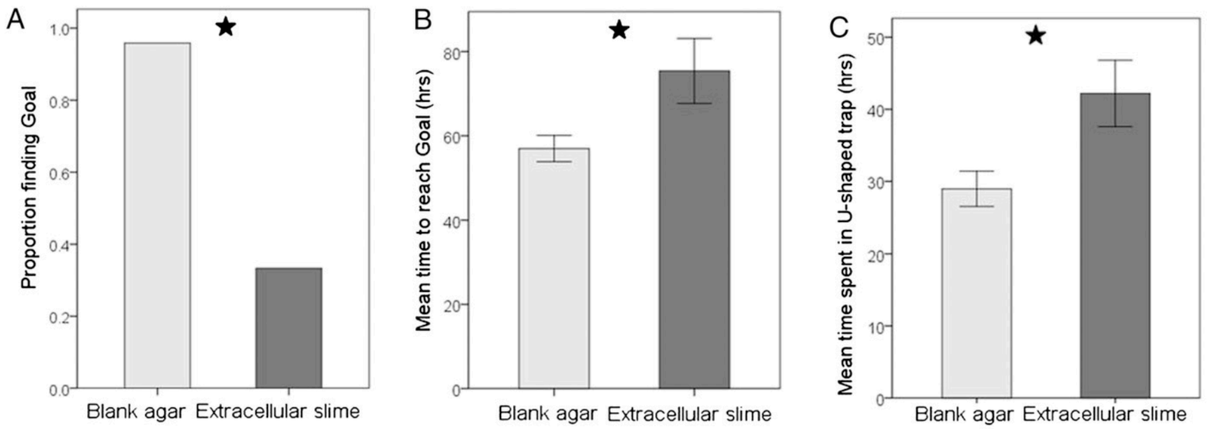


- Arm B contained extracellular slime (naturally secreted by slime molds).
- 39/40 molds chose arm without slime mold.
- Indicates it has been there before.

(Reid et al. 2012)

Spatial memory

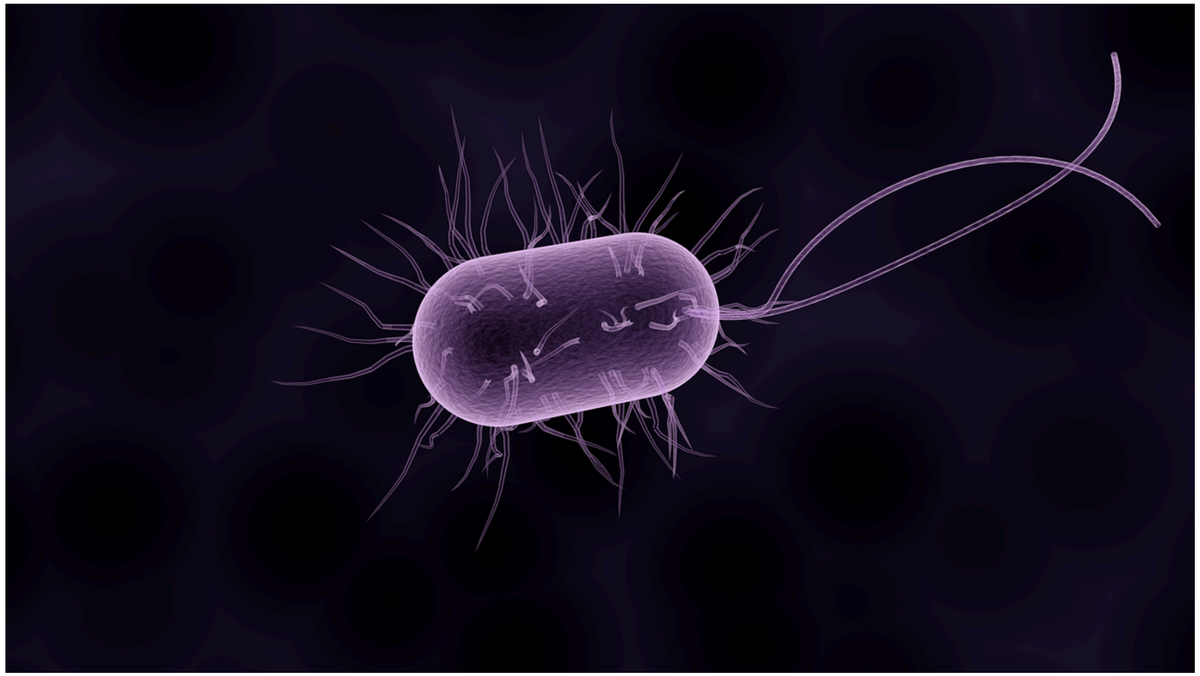


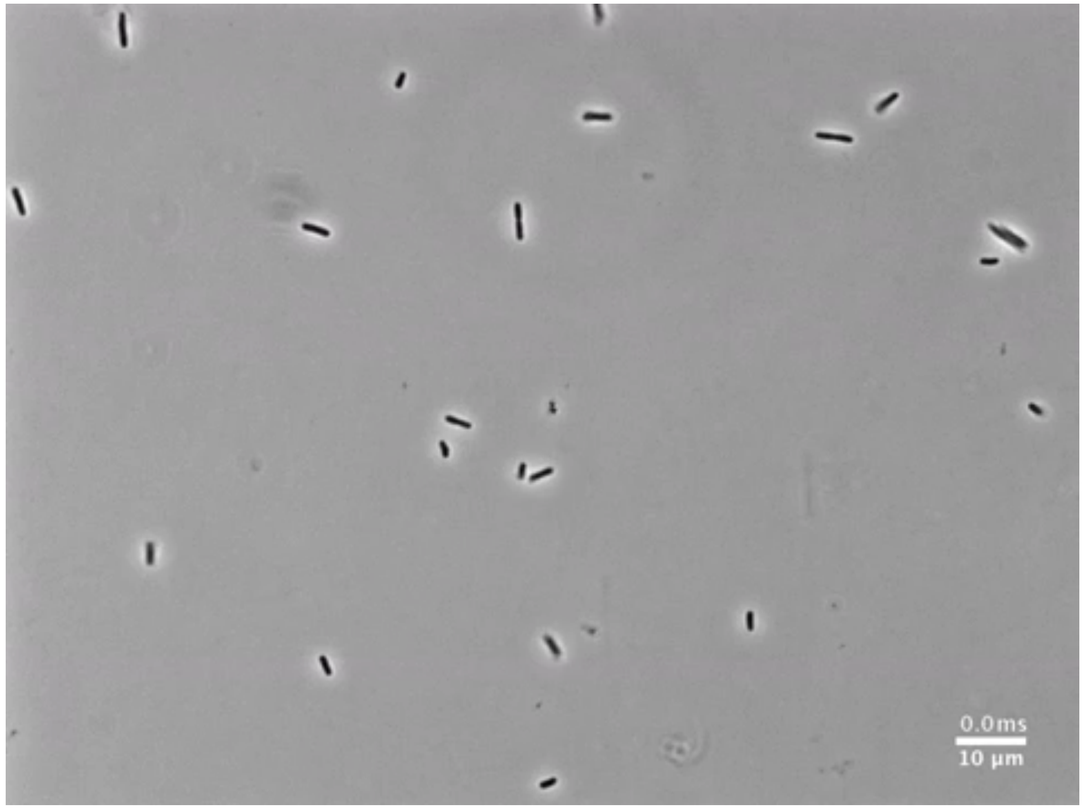


- Presence of extracellular slime impaired slime mold's ability to "solve" the maze.
- Chemical "I've been here" trail.

(Reid et al. 2012)

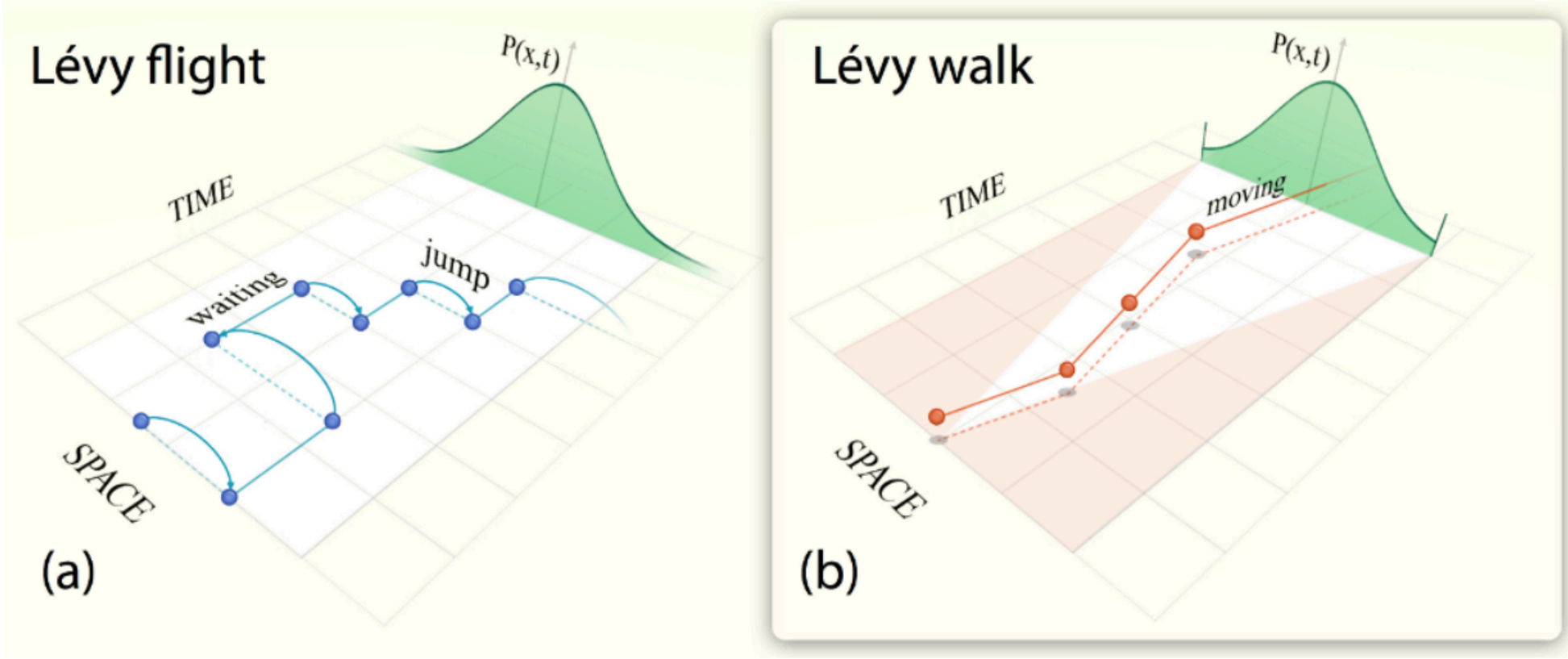
Organism 2: E. Coli





https://www.youtube.com/watch?v=ClDjFTSr4fY

Lévy flights and Lévy walks



(Zaburdaev et al. 2015)

Lévy walk vs. Brownian motion

Random walk in 2D space

$$\theta_i = v_i 2\pi, \quad v_i \sim U(-\pi, \pi)$$

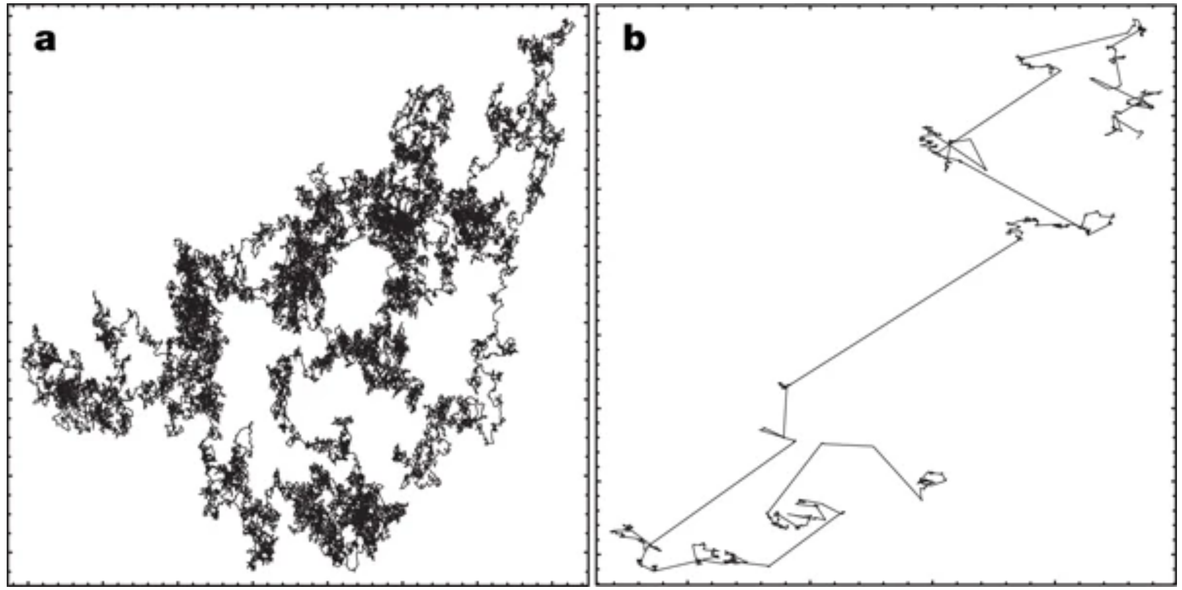
$$\delta_i = u_i^{-\frac{1}{\gamma}}, \quad u_i \sim N(\mu, \sigma)$$

$$x_i = x_{i-1} + \delta_i \cos(\theta_i)$$

$$y_i = y_{i-1} + \delta_i \sin(\theta_i)$$

Brownian motion ($\gamma = 1$)

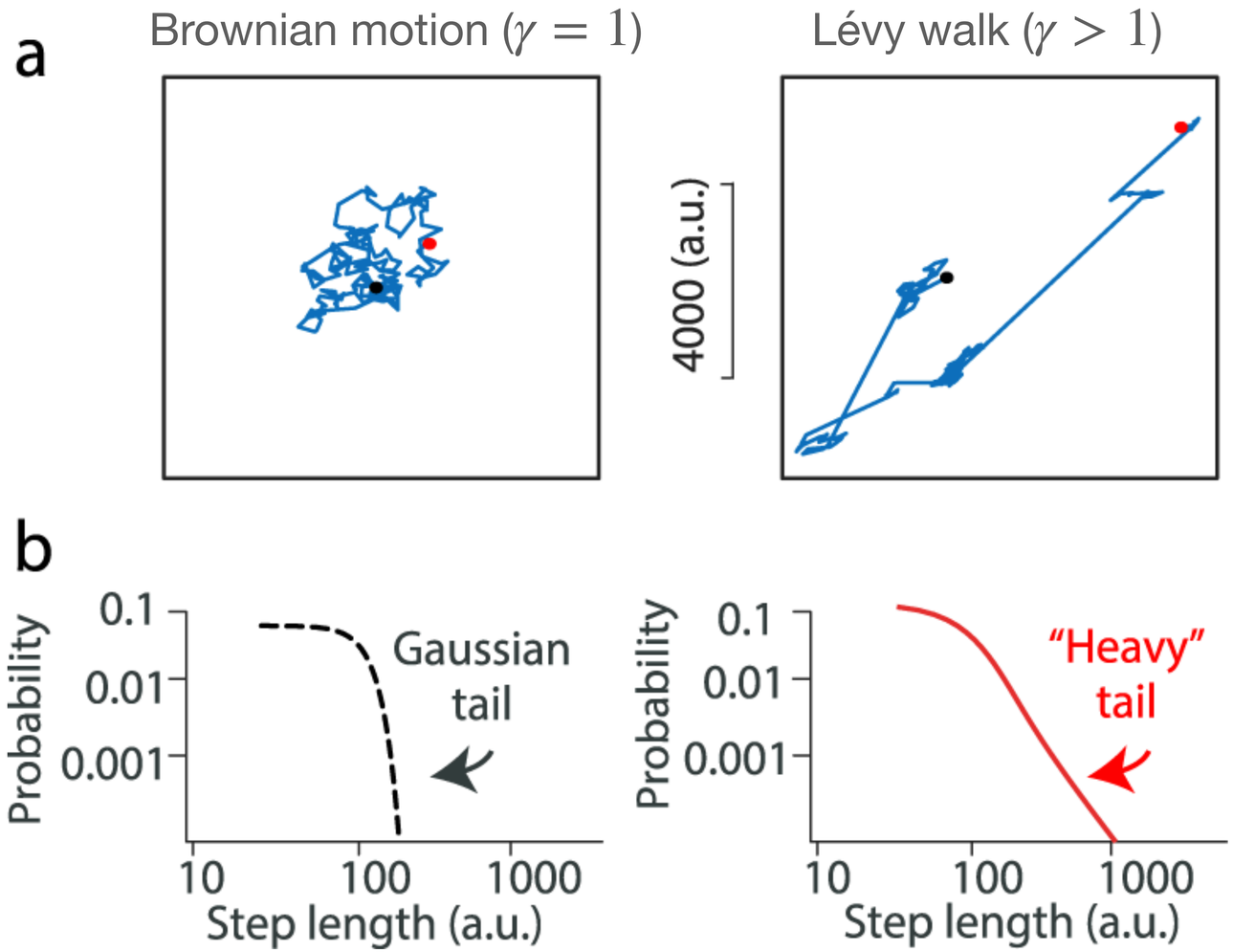
Lévy walk ($\gamma > 1$)



(Barthelemy et al. 2008)

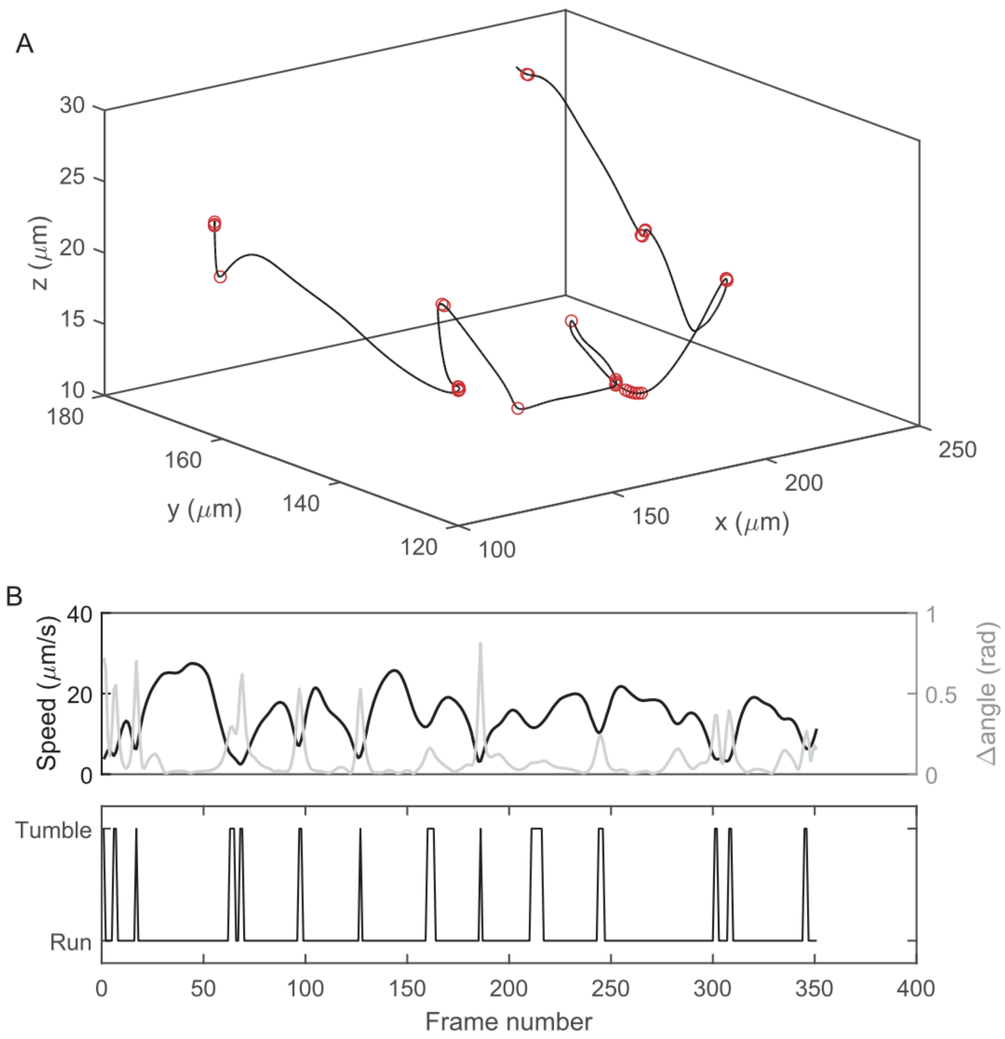
Power Law

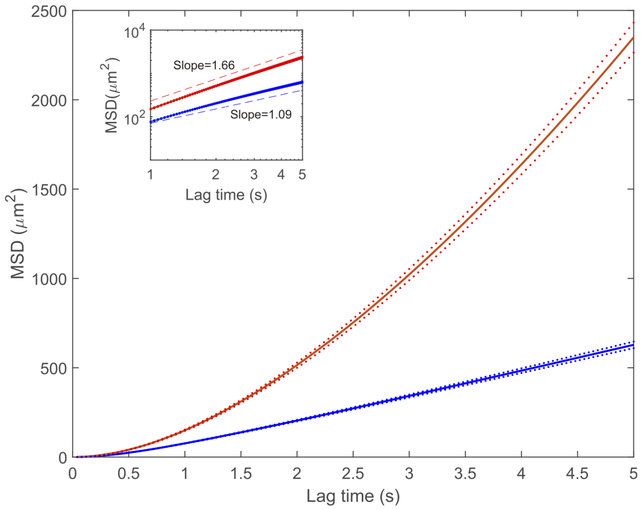
Lévy walks produce probability distributions with “heavy” (aka- long) tails, compared to Brownian motion.

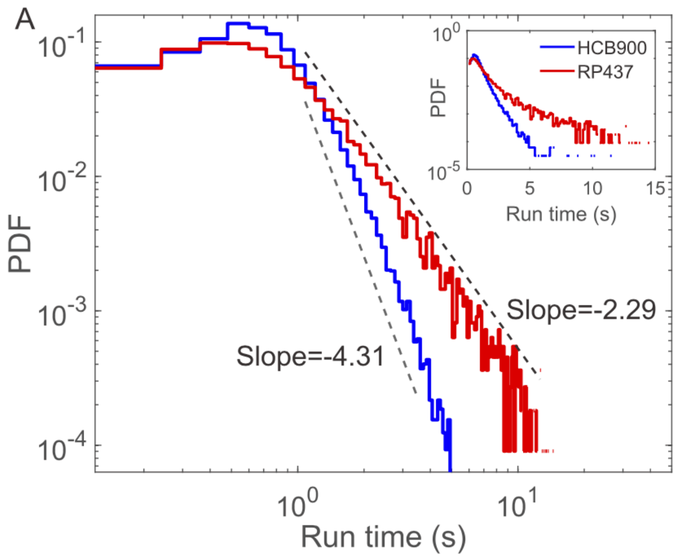


(Liu et al. 2021)

Do *e coli* use Lévy motion to explore?



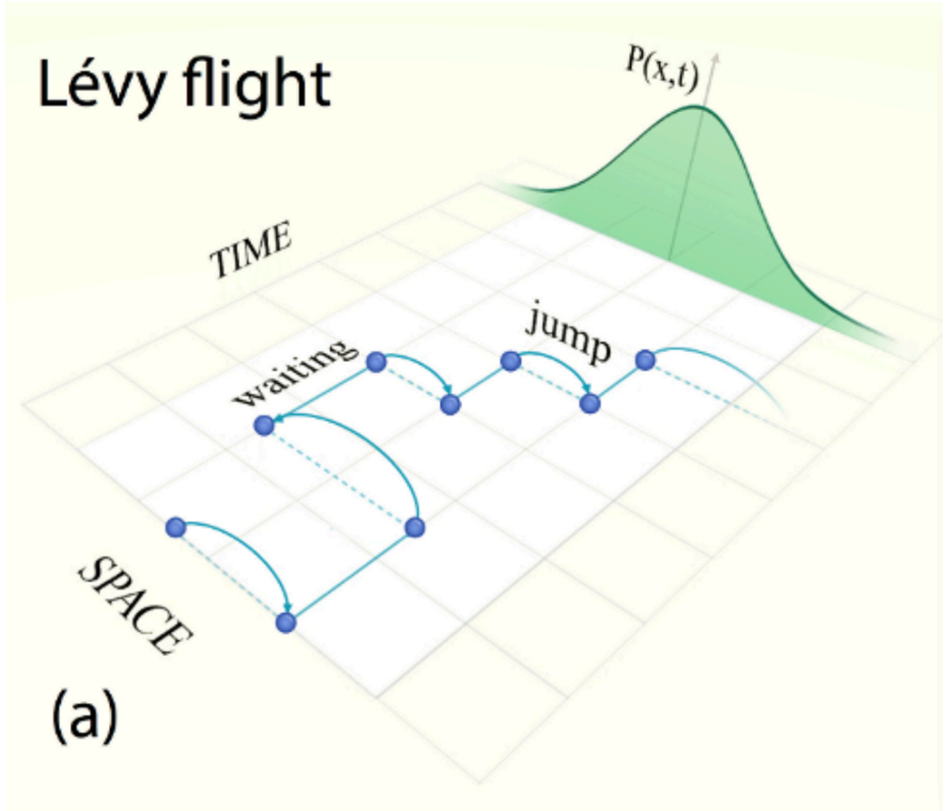


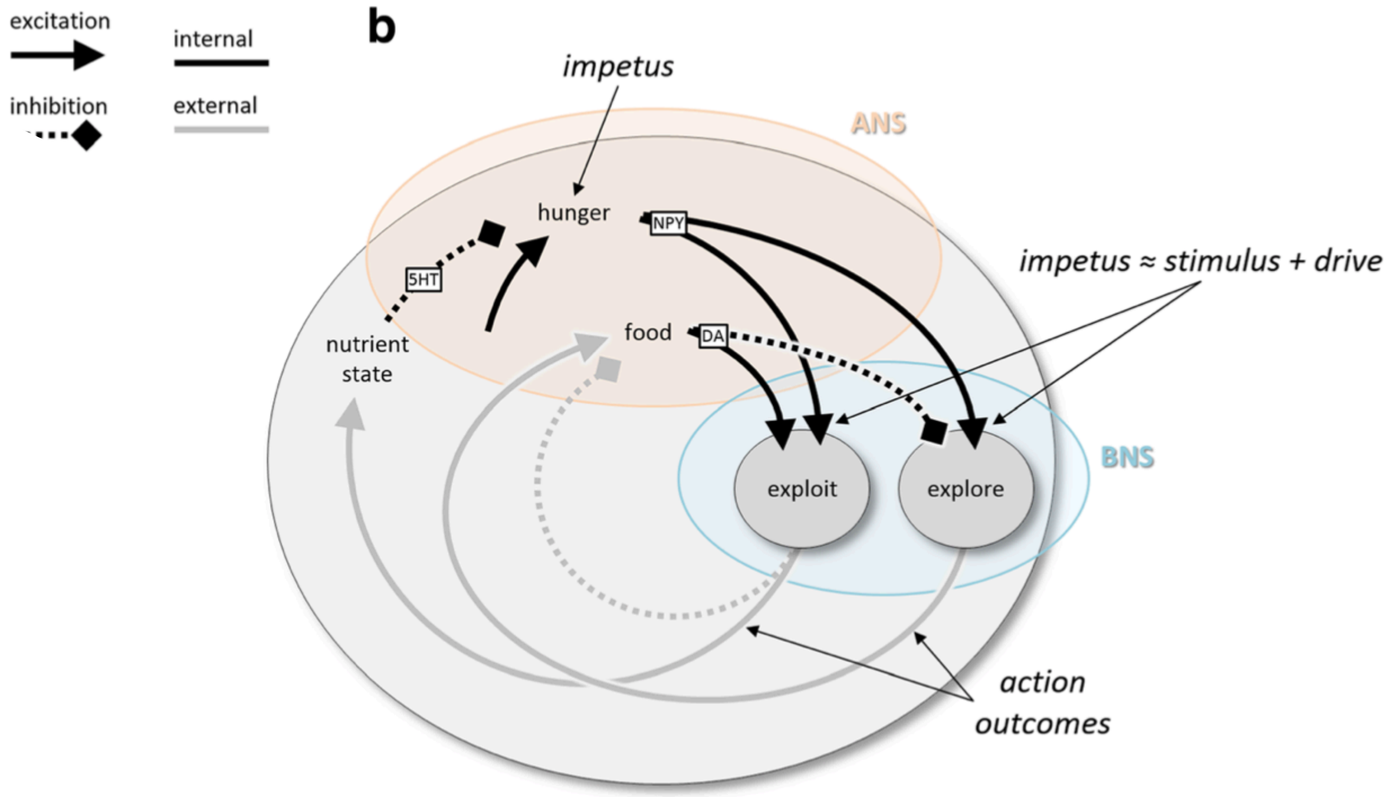


Compared to mutants (HCB900) who lack a critical part of the chemotaxis pathway, wild type *e coli* exhibit super diffusivity in their movements consistent with a Lévy walk process.

(Huo et al. 2021)

Lévy flights as explore-exploit processes





(Cisek 2019)

Take home message

- Organisms without brains can effectively explore.
- They use sensory signals as a drive for movement (slime mold, *e. coli*).
- They find optimal (i.e., shortest) paths through the environment (slime mold).
- They use Lévy flight processes to increase efficiency of random exploration (*e. coli*).

Lab 2: Random exploration

URL: https://github.com/CoAxLab/BiologicallyIntelligentExploration/tree/main/Labs