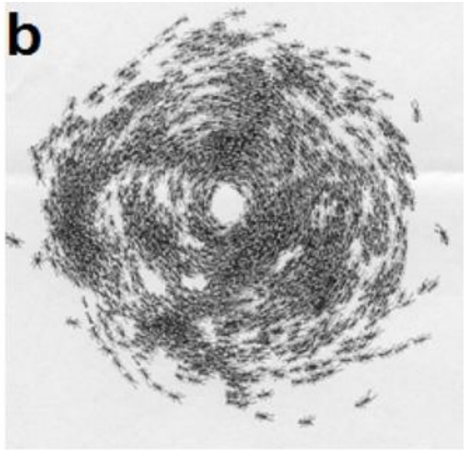
Collective behavior: Summary

- Systems of many similar units interacting in a well-defined manner
- Interactions within a cluster: attraction/repulsion, or more complex combinations
- Behave differently than they would on their own
- Transitions can occur simultaneously, governed by the collective
- Critical behavior of order parameters (average normalized velocity)
- Correlations in space, time across a cluster

locusts

ants



starlings

zebra

Lectures 11, 12

• William Bialek: Fundamental physical limits on the performance of biological systems (2018)
"*for the application of general theoretical principles of physics and information theory to help understand and predict how biological systems function across a variety of scales, from molecules and cells, to brains and animal collectives.*"

• Irene Giardina and Andrea Cavagna: Statistical physics of flocks and swarms (2021)
"*For the incisive combination of observation, analysis, and theory to elucidate the beautiful statistical physics problems underlying collective behavior in natural flocks and swarms.*"

Guiding questions

- Pay attention to the sources, their attributes and “genre”
- What was the scientific breakthrough?
- Can you identify a key insight(s) needed for the breakthrough?
- How do the findings align with or challenge existing models?
- Can you put this work in the context of others in the course? Compare/contrast.
- What are some potential implications of their findings?

Bill Bialek: the questions

What are the physical limits on biological systems, and what are their implications?

Do principles like information flow optimality or maximum entropy govern some biological systems (the brain)?

How do interactions between individual elements in a biological system give rise to population-level properties?

Bill Bialek: the impact

What are the physical limits on biological systems, and what are their implications?

1984

PHYSICS LETTERS 20 August 1984

QUANTUM LIMITS TO OSCILLATOR STABILITY:
THEORY AND EXPERIMENTS ON ACOUSTIC EMISSIONS FROM THE HUMAN EAR

William BIALEK [a,1] and Hero P. WIT [b]

1987

Ann. Rev. Biophys. Biophys. Chem. 1987. 16: 455–78
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PHYSICAL LIMITS TO SENSATION AND PERCEPTION

William Bialek[1]

2005

PNAS

Physical limits to biochemical signaling

William Bialek* and Sima Setayeshgar†

Joseph Henry Laboratories of Physics and Lewis–Sigler Institute for Integrative Genomics, Princeton University, Princeton, NJ 08544

Communicated by Curtis G. Callan, Jr., Princeton University, Princeton, NJ, May 25, 2005 (received for review February 2, 2005)

2007

Cell

Probing the Limits to Positional Information

Thomas Gregor,[1,2,3,4,*] David W. Tank,[1,2,3] Eric F. Wieschaus,[2,4] and William Bialek[1,3]
[1]Joseph Henry Laboratories of Physics
[2]Department of Molecular Biology
[3]Lewis-Sigler Institute for Integrative Genomics
[4]Howard Hughes Medical Institute
Princeton University, Princeton, NJ 08544, USA
*Correspondence: tg2@princeton.edu
DOI 10.1016/j.cell.2007.05.025

Role of noise and sensitivity in setting limits

Bill Bialek: the impact

Do principles like information flow optimality or maximum entropy govern some biological systems (the brain)?

1989

Reading a Neural Code

William Bialek, Fred Rieke, R. R. de Ruyter van Steveninck[1] and David Warland

VOLUME 73, NUMBER 6 PHYSICAL REVIEW LETTERS 8 AUGUST 1994

1994

Statistics of Natural Images: Scaling in the Woods

Daniel L. Ruderman[1,2] and William Bialek[1]

1996

VOLUME 80, NUMBER 1 PHYSICAL REVIEW LETTERS 5 JANUARY 1998

1998

Entropy and Information in Neural Spike Trains

S. P. Strong,[1] Roland Koberle,[1,2] Rob R. de Ruyter van Steveninck,[1] and William Bialek[1]

2000

Neuron, Vol. 26, 695–702, June, 2000, Copyright ©2000 by Cell Press

Adaptive Rescaling Maximizes Information Transmission

Naama Brenner, William Bialek,* and Rob de Ruyter van Steveninck
NEC Research Institute
Princeton, New Jersey 08540

VOLUME 91, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2003

2003

Network Information and Connected Correlations

Elad Schneidman,[1,2,3] Susanne Still,[1,3] Michael J. Berry II,[2] and William Bialek[1,3]

2008

PNAS

Information flow and optimization in transcriptional regulation

Gašper Tkačik[*†], Curtis G. Callan, Jr.[*‡], and William Bialek[‡]

Entropy and information in the context of biological systems

Bill Bialek: the impact

How do interactions between individual elements in a biological system give rise to population-level properties?

2011

J Stat Phys (2011) 144:268–302
DOI 10.1007/s10955-011-0229-4

Are Biological Systems Poised at Criticality?

Thierry Mora · William Bialek

Abstract Many of life's most fascinating phenomena emerge from interactions among many elements—many amino acids determine the structure of a single protein, many genes determine the fate of a cell, many neurons are involved in shaping our thoughts and memories. Physicists have long hoped that these collective behaviors could be described using the ideas and methods of statistical mechanics. In the past few years, new, larger scale experiments have made it possible to construct statistical mechanics models of biological systems directly from real data. We review the surprising successes of this "inverse" approach, using examples from families of proteins, networks of neurons, and flocks of birds. Remarkably, in all these cases the models that emerge from the data are poised near a very special point in their parameter space—a critical point. This suggests there may be some deeper theoretical principle behind the behavior of these diverse systems.

2006

Vol 440|20 April 2006|**doi:10.1038/nature04701** **nature**

Weak pairwise correlations imply strongly correlated network states in a neural population

Elad Schneidman[1,2,3], Michael J. Berry II[2], Ronen Segev[2] & William Bialek[1,3]

Biological networks have so many possible states that exhaustive sampling is impossible. Successful analysis thus depends on simplifying hypotheses, but experiments on many systems hint that complicated, higher-order interactions among large groups of elements have an important role. Here we show, in the vertebrate retina, that weak correlations between pairs of neurons coexist with strongly collective behaviour in the responses of ten or more neurons. We find that this collective behaviour is described quantitatively by models that capture the observed pairwise correlations but assume no higher-order interactions. These maximum entropy models are equivalent to Ising models, and predict that larger networks are completely dominated by correlation effects. This suggests that the neural code has associative or error-correcting properties, and we provide preliminary evidence for such behaviour. As a first test for the generality of these ideas, we show that similar results are obtained from networks of cultured cortical neurons.

2012

PNAS

Statistical mechanics for natural flocks of birds

William Bialek[a], Andrea Cavagna[b,c], Irene Giardina[b,c,1], Thierry Mora[d], Edmondo Silvestri[b,c], Massimiliano Viale[b,c], and Aleksandra M. Walczak[e]

[a]Joseph Henry Laboratories of Physics and Lewis—Sigler Institute for Integrative Genomics, Princeton University, Princeton, NJ 08544; [b]Istituto dei Sistemi Complessi, Consiglio Nazionale delle Ricerche, Rome, Italy; [c]Dipartimento di Fisica, Universitá Sapienza, Rome, Italy; [d]Laboratoire de Physique Statistique de l'École Normale Supérieure, Centre National de la Recherche Scientifique and University Paris VI, Paris, France; and [e]Laboratoire de Physique Théorique de l'École Normale Supérieure, Centre National de la Recherche Scientifique and University Paris VI, Paris, France

Flocking is a typical example of emergent collective behavior, where interactions between individuals produce collective patterns on the large scale. Here we show how a quantitative microscopic theory for directional ordering in a flock can be derived directly from field data. We construct the minimally structured (maximum entropy) model consistent with experimental correlations in large flocks of starlings. The maximum entropy model shows that local, pairwise interactions between birds are sufficient to correctly predict the propagation of order throughout entire flocks of starlings, with no free parameters. We also find that the number of interacting neighbors is independent of flock density, confirming that interactions are ruled by topological rather than metric distance. Finally, by comparing flocks of different sizes, the model correctly accounts for the observed scale invariance of long-range correlations among the fluctuations in flight direction.

Emergent properties, pattern formation

Today's plan

Bialek developing theory for biological systems and emergent properties
https://www.youtube.com/watch?v=UQQLjm0toU8 47:20-84 (38 min)

Break

Discussion of "the questions" based on the video

Bialek emergence in the brain https://www.youtube.com/watch?v=qP_cogP_qR8 (4 min)
Bialek theory for biology, big questions https://www.youtube.com/watch?v=PRli78QkEfQ 11 min
Bialek Living History https://www.youtube.com/watch?v=4myrUPQ2-o4&list=PLHeeH4QC_pZVjTm_Jmffmem57ag4-c6Kh&index=72_ 14 min

Guiding questions

- Pay attention to the sources, their attributes and “genre”
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