The other half of western civilization:
An experiment in freshman science teaching

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William Bialek

Joseph Henry Laboratories of Physics
Lewis-Sigler Institute for Integrative Genomics
Princeton Center for Theoretical Physics
Princeton University

http://www.princeton.edu/~wbialek/wbialek.html
How many cultures?

 Literary intellectuals at one pole— at the other scientists, and as the most representative, physical scientists. Between the two a gulf of mutual incomprehension ... a curious distorted image of each other.

CP Snow, in The Two Cultures and The Scientific Revolution (Cambridge University Press, 1959)

Could there be as large a gulf within science itself?

The “mathematical sciences”
(e.g., physics)

The “non-mathematical sciences”
(e.g., biology)
There is a widespread (almost trite) sentiment that this gulf between the physical and biological sciences needs to bridged, and that now is the right time to do this.

“There’s something happening here, what it is ain’t exactly clear ...”
(Stephen Stills, Buffalo Springfield, 1967)

“There is much less agreement about what all of this actually means, even in principle.

“The biology of the 21st century will be a more quantitative science.”
“The greatest challenges need to be met by interdisciplinary collaborations.”
“The genome and the computer have revolutionized how we do biology.”
“As we address system-level questions, we move beyond what we can do intuitively, and need more mathematical tools.”
“Mathematics will be biology’s new microscope.”
Before we have a theory, let's look at the data ...
The difference between physics and biology is not just that physics “makes more use of quantitative methods” (although it does).

In physics, we are searching for an understanding of Nature that we can summarize in mathematical terms.

Mathematics is not an optional accessory, nor is it merely a tool alongside many others.

“La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l’universo), ma non si può intendere se prima non s’impara a intender la lingua, e conoscer i caratteri, né quali è scritto. Egli è scritto in lingua matematica, e i caratteri sono triangoli, cerchi, ed altre figure geometriche, senza i quali mezi è impossibile a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un’oscury laberinto.”

~“The book of Nature is written in the language of mathematics.”

(Galileo Galilei, 1623)
Two related but distinct goals

Educate biologists who find it natural to do quantitative experiments, sophisticated analyses of their data, and meaningful comparisons with theory (because biology is so big, even incremental progress can have a big impact) (perhaps we shouldn’t be shy to say “make biology more like physics”)

Educate physicists who find it natural to bring the “physicist’s style of thought” to study a broader class of systems, including biological systems (this clearly can’t be accomplished by learning less physics!)

These goals are very different at the graduate level.

Given the state of biology education today, meaningful progress on the first goal is hard to achieve if you wait until graduate school.

Similarly, if you wait too long to start work on the second goal one has to face large barriers of language and habit

So: start at the beginning!
Boundary conditions

First, do no harm.

For the first year, we want to create an alternative to the combination of freshman physics and chemistry ...

While we want lots of connections to biology, we don't want the responsibility of communicating the factual content of intro bio courses (save this for a sophomore follow up course).

All relevant departments need to agree that we have delivered the equivalent of freshman physics and chemistry (+ a little CS) at some level.

Thus, students from our course will have access to the full range of majors.

As in our physics courses for majors, we build on previous mathematical experience, but will teach some of what we need as we go along.

We simplify our problem by taking students who have had a calculus course at the level of AP Calculus BC.
You can’t satisfy the boundary conditions without genuine collaboration among the departments.

In particular, a top down initiative won’t work.

(... There’s a man with a gun over there, telling me I got to beware ...)

We had the good fortune to have a group of faculty from all the relevant departments who were interested in rethinking freshman science education in the broadest sense. We worked from a “zero base budget.”
Faculty

W Bialek (physics)
CG Callan (physics)
D Botstein (molecular biology)
B Chazelle (computer science)
JT Groves (chemistry)
M Hecht (chemistry)
L Hodges (teaching center)

L Kruglyak (evolutionary biology)
D Marlow (physics)
J Rabinowitz (chemistry)
C Schutt (chemistry)
O Troyanskaya (computer science)
EF Wieschaus (molecular biology)

Lewis-Sigler fellows

M Dunham, E Pearlstein, WS Ryu & EM Schoetz (experimentalists)
M Desai & M Kaschube (theorists)

Plus ... many teaching assistants from all departments
Freshman physics topics

- Newtonian mechanics
- Electricity and magnetism (up to Maxwell)
- Waves
- Thermodynamics and a little statistical physics
- (sometimes) “Modern physics”

Freshman chemistry topics

- Thermodynamics and chemical equilibrium
- Reaction kinetics
- A tour of the periodic table
- Chemical potential, electrochemistry, ...
- Orbitals, bonds, ...

There are obvious commonalities, and some more subtle relationships through the common mathematical structures

Can we organize around these more general ideas?
What kinds of mathematical structures do we use in describing nature?

**Functional relations**

\[ V = IR, \quad Q = CV, \quad F = -kx, \quad F = -\gamma v, \ldots \]

**Dynamical models (differential equations)**

Elements of classical mechanics (more viscosity than usual!), chemical kinetics (including enzymes, approximations), ... stability and response in genetic switches, resonance in the cell membrane, ...

**Probabilistic models**

Boltzmann distribution, connections to thermodynamics (more complex examples, e.g. protein folding), but also genetics, ...

**Fields**

Electricity and magnetism, but also diffusion, ... pattern formation in development, ...

**The quantum world**
Six weeks on probabilistic models

Genes, combinations and probability (with some inference)
Gas laws and the Boltzmann distribution
Brownian motion and the reality of molecules
Emergence and approximation
Chemical equilibria and thermodynamics
Entropy, from Carnot to Shannon

we aimed high: mathematical sophistication at the level of our honors freshman physics course

\[
\langle E \rangle = \frac{1}{Z} \sum_s E_s \exp(-\beta E_s) \\
= \frac{1}{Z} \sum_s \left[ -\frac{\partial}{\partial \beta} \exp(-\beta E_s) \right] \\
= -\frac{1}{Z} \frac{\partial}{\partial \beta} \sum_s \exp(-\beta E_s) \\
= -\frac{1}{Z} \frac{\partial}{\partial \beta} Z
\]

a. Suppose that we make one measurement of the velocity of a molecule and find the results \( v_x = v_1 \). What is the value of the temperature that is most likely to have generated this data point?

b. Let us make measurements on two molecules, with results \( v_1 \) and \( v_2 \). What is joint the probability distribution of \( v_1 \) and \( v_2 \)? Generalize this to making \( n \) measurements.

c. Given \( n \) measurements \( v_1, v_2, \ldots, v_n \), what is the value of the temperature that is most likely have generated this whole set of data?
Getting some help from the computer: Exploring the combinatorics that leads to the Boltzmann distribution

In MATLAB, we can let `states` be 1000 samples of a list of 10 numbers, so it is a $10 \times 1000$ array. To pick the energies we use `rand`, with a little trick to turn the continuous distribution into random integers from 1 to 100. We have to try many times in order to be sure that we will find 1000 examples that meet our criterion for the total energy.

```matlab
Nsamples = 1000;
states = zeros(10,Nsamples);
k = 1;
for N = 1:1e8;
    if k <= Nsamples;
        s = ceil(100*rand(10,1));
        if sum(s) == 200;
            states(:,k) = s;
            k = k+1;
        end;
    end;
end;
```

1000 samples of a "gas" with 10 molecules, total $E = 200$
Meanwhile, in the lab ...

Delbrück-Luria experiment with yeast

we meet weekly to keep labs, lectures, problem sets, ... all tied together

Direct measurements of Brownian motion
This year: 49 students in the freshman class

~1/3 of Juniors majoring in Physics came through our course

~1/2 of students so far major in Molecular Biology, instantly the “go to” people for quantitative analysis, changing what gets done in the labs

and this is after the final exam

The pioneers (now seniors)