What Can Physics Say About Life Itself?

Science at the Interface of Physics and Biology

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March 9, 2011

Source: UIUC, Wikimedia
Our universe in length scales

(in meters)

- $10^{-35}$: Planck length (string theory)
- $10^{-18}$: LHC, electroweak
- $10^{-15}$: Proton, nucleus
- $10^{-10}$: Atoms
- $10^{-8}$: Molecules, proteins
- $10^{-5}$: Cells, bacteria
- $10^{-2}$: Insects
- $1$: Humans
- $10^{2}$: Earth
- $10^{6}$: Solar system
- $10^{12}$: Milky Way
- $10^{20}$: Local Group
- $10^{23}$: Observable universe
- $10^{27}$: In meters
Our universe in length scales

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Humans $1$  

Earth $10^6$

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Observable universe $10^{27}$
Our universe in length scales

Physics (particle)  
FUNDAMENTAL  
Condensed matter, chemistry, biology  
EMERGENT  
Physics (astro and cosmology)  
FUNDAMENTAL
Question:

Why do we have to think about biological phenomena in the intermediate regime so differently?
So why is biology so exciting NOW? (for physicists)

Lots of reasons! But.....

A new data revolution

“High-throughput”: HUGE amounts of new data!
Why biology? DNA Sequencing

DNA sequences quickly and cheaply

Now every major institution has sequencers -- complete genomes are routinely published

Source: Wikimedia
Why biology? Incredibly interdisciplinary

- Mathematicians
- Computer scientists
- Engineers
- Physicists
- Chemists
- Traditional biologists

“Biological physics”
“Biophysical chemistry”
“Mathematical biology”
“Quantitative biology”
“Computational biology”
“Biochemistry”
“Biophysics”
Why biology?
Opportunity for impact

Questions of basic science and model-building

Collaboration/interplay between theory and experiment

Real applications in engineering and medicine
What kinds of physicists are interested in biology?

Traditionally, many come from other fields:

★ Statistical physicists, complex systems, nonlinear dynamics
★ Condensed matter physicists (theory and experiment)
★ Particle physicists/string theorists

But biophysics is now becoming an established field of physics on its own
What do physicists have to offer in biology?

Unique combination of scientific intuition and mathematical rigor

Model-building and data analysis skills

An approach different from that of traditional biologists

Interested in understanding general properties, not just details of specific systems
"Biologically-inspired Physics" (BIP)

Physical properties of structures and processes in biology

★ “Soft” condensed matter: polymers, lipids, gels, foams (non-quantum)
★ Polymer physics: DNA, proteins
★ Bacterial motility and molecular machines

Interesting physics, but what does it say about biology?
Classic BIP: DNA physics

What are physical properties of DNA?


http://video.google.com/videoplay?docid=1167826811281154386#
DNA structure =  “chromatin”

Questions of physics, geometry, topology

Source: Genome.gov
Protein folding

How do proteins fold?

Levinthal paradox: how do they fold so quickly?

Predicting structure from sequence

Source: Wikimedia
Bacterial chemotaxis

How do bacteria detect changes in their environment and modify their movements?


Molecular machines

Kinesin: a “molecular mule”

Transports molecules along microtubule

Can we build a physical model?
“Physics-inspired Biology” (PIB)

Mathematical models of biological systems in analogy with physics

Ideas borrowed from statistical mechanics, condensed matter

Appealing models, but can we incorporate any real physics?
Genetics and evolution

How do populations of genes change over time?

Ideas from statistical mechanics:

- Diffusion
- Markov chains
- Branching processes
- Spin systems, Ising model
- Path integrals

Path integrals?  

Graph theory?
Systems biology and neuroscience

Systems biology

★ Networks of regulatory systems in organisms
★ Big sets of PDEs with huge parameter spaces
★ Questions of robustness, steady states, evolution

Neuroscience: circuits and networks
Linking BIP and PIB: What is Rutgers doing?

Physical models of biological structures

Phenomenological model of biological processes

A unified theory of physics and biology?
Biophysical models of evolution

Simple model of protein thermodynamic stability

Free energy of folding:
\[ \Delta G = G_f - G_u \]

Probability of being folded:
\[ p_f \]
Biophysical models of evolution

Mathematical (phenomenological) model of protein evolution

Build this model using protein free energies.....

.....now you have a model of evolution in terms of physics!
Biophysical models of evolution

What can protein physics tell us about evolution and vice versa?

Physical properties constrain evolution

Evolutionary data implies physical properties
\[ \dot{\rho}(t) = -\frac{i}{\hbar}[H, \rho(t)]_\pm - \frac{k_s}{2}[Q^S, \rho(t)]_\pm - \frac{k_T}{2}[Q^T, \rho(t)]_\pm \]
Biophysical models of evolution

A question of basic science: linking physics and biology

Not purely academic:

- Protein engineering
- Nanostructures, self-replicating materials, drug design, biofuel synthesis
The future?

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Parting thought from Steven Weinberg
(1979 Nobel Prize in physics)

“Four golden lessons” for students
(Nature 426, Nov. 27, 2003) -- read it!

“Go for the messes -- that's where the action is.”