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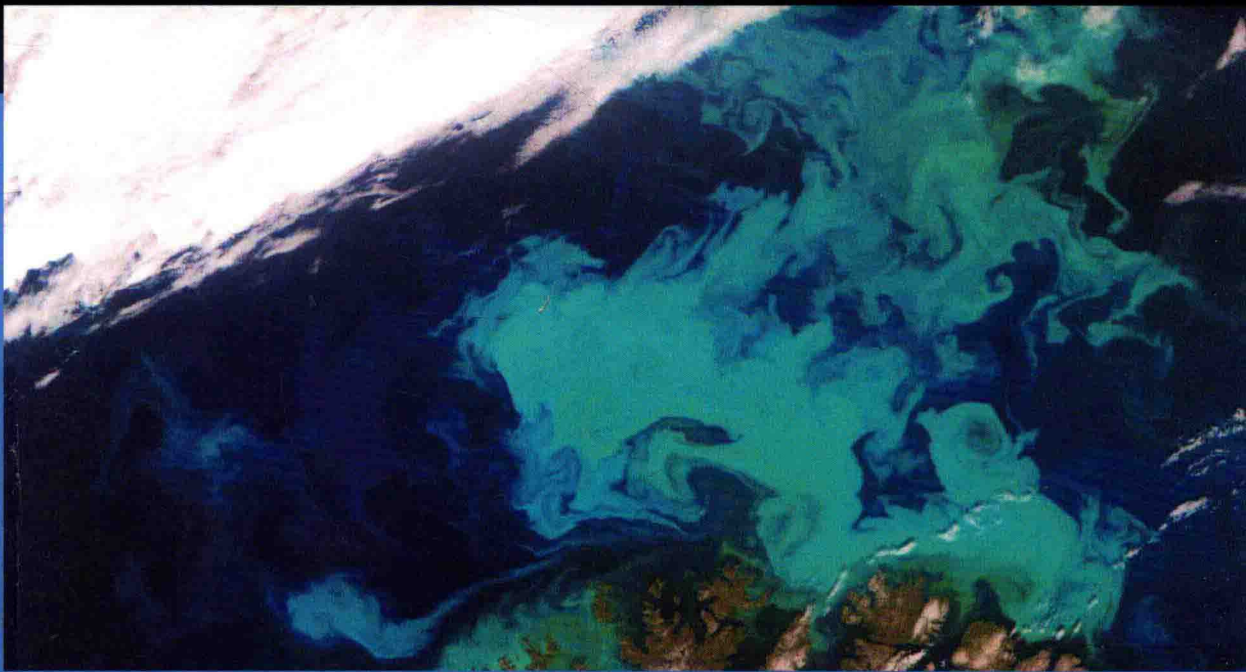
J. Claycomb, Jonathan Quoc P. Tran

# Introductory Biophysics
## Perspectives on the Living State

# 生物物理学导论



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# INTRODUCTORY BIOPHYSICS

## PERSPECTIVES ON THE LIVING STATE

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*Dedicated to the memory of*
*John Vay*

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# Introduction

Physics is the most basic natural science. It is the lowest-level science on a tree diagram representing the natural sciences. Other sciences such as chemistry and biology are higher-level sciences. Now it is possible to begin on one of the natural science branches and proceed quite a distance without knowledge of the more basic physical principles such as Newton's laws and gravitation. General physics, for example, is rarely a prerequisite for introductory biology and chemistry. To sprout new branches in our understanding of nature, and biology in particular, the tools of basic physics and chemistry are often required.

One goal of this textbook is to introduce biophysical theory concurrently with computer simulation. Another goal is to emphasize several important themes such as the role of entropy and the ubiquity of the statistical Boltzmann factor describing many aspects of the living state from the establishment of membrane potentials to the sedimentation of cell cultures. A key perspective of the textbook considers life in relation to the universe as a whole.

Additional computer simulation examples and exercises in the text and on the companion CD enable modeling of biophysical phenomena such as diffusion, establishment of membrane potential, bioimpedance, and the electrical response of cells and organelles to external fields. Dynamical models include the propagation of action potentials, nonlinear oscillations in population dynamics, and DNA vibrational modes. The formation of fractal structures, branching networks, and patterns in biology are also simulated. Contact with simulation methods further reinforces biophysical theory and strengthens the connection between physics and the life sciences.

Topics are arranged in increasing size scale and complexity. Chapters 1 and 2 give an introductory overview of biological structure and molecular forces. Chapters 3 through 6 cover heat transfer, thermodynamics, statistical mechanics, and diffusion, which play important roles in the biological domain. Chapter 7 covers fluid dynamics and the motion of bodies in fluid media. Bioenergetics, molecular motors, and the light absorption of biomolecules are discussed in Chapter 8. Chapters 9 through 11 discuss electrical and mechanical aspects of biophysics, including the passive response of cells and tissue to electric fields, field-induced stresses in biomaterials, and the propagation of action potentials in nerve cells. Biomagnetism and magnetic measurements are discussed in Chapter 12. Nonlinearity, chaos, and complexity in the life sciences are covered in Chapters 13 and 14. The textbook concludes with an introduction to astrobiology in Chapter 15.

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# Table of Contents

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# 1 Building Blocks and Structure



## 1.1 Atoms and Ions

### 1.1.1 Subatomic Particles

All matter essential to life is made up of atoms consisting of protons, neutrons, and electrons. The electron is a stable particle belonging to a class of subatomic particles known as fermions. The electron is elementary and without internal structure. Table 1.1 gives a list of elementary particles according to the standard model of particle physics. Protons and neutrons are composite particles made out of combinations of three up (u) and down (d) quarks. The proton is (uud) while the neutron is (ddu). The four other quarks: strange (s), charm (c), top (t), and bottom (b) do not form stable particles and therefore do not participate in the physics of the living state.

Another particle essential to life is the photon ($\gamma$) that is a massless member of the Boson class of particles. Without the photon, energy could not travel from the Sun to

**Table 1.1 Particles of the Standard Model**

| Fermions | | | Bosons |
|---|---|---|---|
| $u$ | $c$ | $t$ | $\gamma$ |
| $d$ | $s$ | $b$ | $Z$ |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | $W$ |
| $e^-$ | $\mu$ | $\tau$ | $g$ |

the Earth and warm our planet. Plants absorb photons to produce adenosine triphosphate (ATP) and to fix carbon that is consumed by more complex organisms on the food chain such as humans.

In Paul Dirac's theory of relativistic quantum mechanics, antiparticles were predicted that were later discovered in cloud chamber experiments. It turns out that for every particle species in nature there is a corresponding antiparticle, although antimatter is quite scarce, at least on Earth. Antimatter plays a key role in the strong nuclear force through the exchange of $\pi$ mesons. These mesons are quark–antiquark pairs exchanged between nucleons binding the nucleus together. Antimatter is therefore essential for the existence of stable atoms and hence, life. Antimatter is also employed in medical imaging using positron emission tomography (PET) where the positron $e^+$ is the positively charged antiparticle of the electron. Gamma rays are detected in PET scans that are produced by the annihilation of matter and antimatter according to the reaction $e^+ + e^- \rightarrow 2\gamma$. From Einstein's mass energy relation and the energy of each photon $E = hf$ with $f\lambda = c$, the wavelength of the gamma rays emitted in PET are $\lambda = h/m_e c = 2.43$ pm.

The neutrino ($\nu$), or "little neutral one," predicted by Wolfgang Pauli, is a participant of beta decay and other nuclear reactions. Roughly $10^{12}$ solar neutrinos pass through our bodies each second. Neutrinos are weakly interacting, so this rate does not change during the night as neutrinos pass straight through the Earth, only very occasionally interacting with matter. Without neutrinos, nuclear reactions essential to stars would not take place. The little neutral one is therefore essential for life in this regard.

The gluon ($g$) is a key participant in the strong nuclear force binding quarks in nucleons and mesons. Other particles of the standard model may not contribute directly to the physics of the living state but may be a natural consequence of a universe capable of sustaining life.

Highly energetic subatomic particles in cosmic rays can also influence life processes by breaking molecular bonds and causing genetic mutations. Fortunately, the Earth's atmosphere serves to greatly attenuate the flux of cosmic rays. The ozone layer is especially important in absorbing harmful solar ultraviolet radiation. Astronauts in space habitats are more vulnerable to solar protons that can cause health problems if received in excessive doses. Solar flares and coronal mass ejections can generate lethal

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