

# THE LIVING CLOCK

The background is a complex collage of green and blue-toned images. It includes a detailed view of a cell membrane with various proteins and channels, a stylized human hand with fingers spread, a vertical stack of horizontal lines resembling a ladder or a data structure, and several stylized, glowing green eyes with long eyelashes arranged vertically on the right side.

*The  
Orchestrator  
of  
Biological  
Rhythms*

JOHN D. PALMER

A detailed illustration of a crab is positioned in the lower-left quadrant of the cover. The crab is shown from a top-down perspective, with its legs and claws clearly defined. The illustration is rendered in a dark, textured style that blends with the overall green and blue color palette of the cover.

# THE LIVING CLOCK

OTHER BOOKS ON BIOLOGICAL RHYTHMS  
BY JOHN PALMER

*Biological Clock: Two views* Academic Press, New York, (with Frank A. Brown, Jr. and J. Woodland Hastings)

*Biological Clocks in Marine Organisms: the Control of Physiological and Behavioral Tidal Rhythms* Wiley (InterScience), New York.

*An Introduction to Biological Rhythms* Academic Press, New York.

*The Biological Rhythms and Clocks of Intertidal Animals* Oxford University Press. New York.

# THE LIVING CLOCK



*The Orchestrator of Biological Rhythms*

*John D. Palmer*

OXFORD  
UNIVERSITY PRESS

2002

**OXFORD**  
UNIVERSITY PRESS

Oxford New York  
Auckland Bangkok Buenos Aires Cape Town  
Chennai Dar es Salaam Delhi Hong Kong Istanbul Karachi Kolkata  
Kuala Lumpur Madrid Melbourne Mexico City Mumbai Nairobi  
Sao Paulo Shanghai Singapore Taipei Tokyo Toronto

and associated companies in  
Berlin Ibadan

Copyright © 2002 by Oxford University Press, Inc.

Published by Oxford University Press, Inc.  
198 Madison Avenue, New York, New York 10016

Oxford is a registered trademark of Oxford University Press

All rights reserved. No part of this publication may be reproduced,  
stored in a retrieval system, or transmitted, in any form or by any means,  
electronic, mechanical, photocopying, recording, or otherwise,  
without the prior permission of Oxford University Press.

**Library of Congress Cataloging-in-Publication Data**

Palmer, John D., 1932–

The living clock / John D. Palmer.

p. cm.

Includes bibliographical references and index.

ISBN 0-19-514340-X

1. Chronobiology—Popular works. I. Title.

QP84.6 P35 2002

571.77—dc21

2001034011

1 3 5 7 9 8 6 4 2

Printed in the United States of America  
on acid free paper

*To my wife, Carla*

*This page intentionally left blank*

## ACKNOWLEDGMENTS

To the many who have advised and helped me in so many ways in this endeavor, I thank all of you. Particular recognition and thanks go to Harold Dowse, Lawrence Feldman, Judith Goode-nough, Marc Roussel, Theodore Sargent, the entire library staff of the Marine Biological Laboratory at Woods Hole Massachusetts, the anonymous reviewers, and to my editor, Kirk Jensen. Blame them for any mistakes (just kidding).

Special thanks to the Digital Corporation (R.I.P.) for having the forethought to give my ancient computer (used to write this book) the where-withal to sail unhampered into the new millennium.

*This page intentionally left blank*

# CONTENTS

<i>Preface</i>	<i>xi</i>
<i>Chapter 1. Introduction to Rhythms and Clocks</i>	1
<i>Chapter 2. Human Rhythms: Basic Processes</i>	11
<i>Chapter 3. Rhythmic Pharmacology</i>	37
<i>Chapter 4. Jet Lag can be a Drag</i>	45
<i>Chapter 5. Daily Rhythm in Single-Cell Organisms</i>	69
<i>Chapter 6. Rhythms in Shore Dwellers</i>	77
<i>Chapter 7. Some Animal Rhythms</i>	93
<i>Chapter 8. A Few Plant Clocks</i>	111
<i>Chapter 9. Denouement: The Living Clock</i>	123
<i>Notes</i>	145
<i>Suggested Readings</i>	149
<i>Figure Credits</i>	157
<i>Index</i>	159

*This page intentionally left blank*

## PREFACE

I sat down at a window seat in the last row of the plane and grumbled at the certainty that I would be served dinner last. I opened my attache case, pushed aside a giant land crab there in a plastic bag, and took out some work to do. Under my seat was a box containing 150 crabs that I was also taking back to my university for use in research. Soon a woman in a business suit—a CEO, I learned later—sat down in the aisle seat and said, “What a day, a drink will really hit the spot.” I had been in the field for weeks and agreed in silence. The last passenger to board was a coed radiating heat from trying to squeeze a month of beach time into a week-long spring break in Florida. She took the seat between the business woman and myself.

The CEO could not resist asking about the scratching sounds coming from the box under my seat. I explained that crabs have within their bodies a living clock, in essence, roughly the same one humans possess, and that I was a biologist studying their behavior. By the time the drink cart finally reached us I was deep in discussion with the people in earshot around me.

I explained to the group that the crab in my attache case was special (at least to me). In the lab, in the absence of any clues to the passage of time, it sat around almost motionlessly all day, but at 6 P.M. every evening it began to run around in its container and continued to do so much of the night. By using its living clock it was able to precisely meet this starting time. In recognition of his impressive punctuality I had named him “Big Ben.”

We landed at Kennedy Airport at 7 P.M., and forgetting about the crab, I opened my attache case to replace the work I had taken out earlier. At 6 P.M. Big Ben had, of course, torn out of the plastic bag. With his two ominous claws, each half the size of a lobster’s, open wide and at the ready, he charged toward the coed, and amazingly, she did a *grand jeté* over people into the aisle. Big Ben followed, scrambling over the CEO’s lap with me in

pursuit. A colorful ending to my lecture, one dramatically driving home the point of living-clock-controlled behavior.

The story above is—in a roundabout way—a reason for the existence of this book. As a marine biologist I travel to lots of places around the world, and fellow travellers usually ask what I do for a living. When I tell them, their first question is, “Do you really get paid to do that?” The answer is yes, but then they want more and more information. They are fascinated to hear that each of them have living clocks within their bodies, as do all plants and animals. People’s uniform interest in the subject, plus the importance of the topic, finally convinced me that I should try to share this information with the reading public—thus the volume you now hold in your hands.

The book is written for nonscientists. While having had one good introductory course in biology will ease your understanding, it is not a requirement. The presentation style is light, and biological terminology is held to an absolute minimum. The chapters are short and can pretty much stand alone; thus readers can stop and contemplate as desired. The book is somewhat autobiographical: I’ve worked in this field for nearly 40 years, and I still maintain my fascination and enthusiasm for the subject.

These clocks within us are very important. They determine the basic rates (for example, intensity or vigor) at which a great many of our fundamental body processes run. They do this automatically so we are oblivious to their presence until we fly to new time zones; then jet lag symptoms signal our timepieces’ existence, actions, and temporary “unhappiness.”

All plants and animals have these timepieces; living clock control is ubiquitous throughout the organic world. Thus, if we are to truly understand living things we must comprehend their clocks. Until this task is accomplished, humanity will lack an exceedingly important key to understanding life. This book is an attempt to give readers a leg up in that direction.

The clock works so subtly that its existence was not foreseen. It was finally recognized in the early part of this century, but only sporadic interest followed for many years. In fact, the majority of scientists became convinced fully of the clock’s existence not very long ago. Biologists still do not understand completely how the timepiece works, but we are rapidly closing in on it; and when the escapement mechanism is finally deciphered, a Nobel Prize should be the reward for the discoverer(s). Lest you think I exaggerate, here is a second opinion. Once each year the American Association for the Advancement of Science publishes the “Breakthroughs of the Year.” For two consecutive years new discoveries about the living clock made that organization’s short, most impressive list.

Clearly, scientists have come to see the importance of the living clock. Hopefully the public will follow their lead—they should: This clock is synonymous with life itself.

*John D. Palmer*  
*University of Massachusetts*  
*Amherst, Massachusetts*

*This page intentionally left blank*

O N E

## INTRODUCTION TO RHYTHMS AND CLOCKS

THE RHYTHMIC MIGRATIONS OF EUGLENA  
A MICROSCOPIC PLANT/ANIMAL

I stood on the famous cast-iron Clifton suspension bridge—built in 1845 by Isambard Kingdom Brunel—looking down on the River Avon. A newcomer to this part of southern England would never suspect that the river below was the terminus of the same quaint, willow-tree margined stream that flows though Shakespeare's Stratford. Here, where it empties into the Bristol Channel, it is (or hopefully was, the year was 1962) a highly polluted, turbid effluent from upstream humanity. Another difference is that this stretch of the river experiences the second highest tidal exchange on earth: something like 43 feet depending on the day of the month. As I stared down from my lofty overlook, standing in the exact spot where modern bungee jumping would be born in 1979—with the mini-car traffic barely missing my backsides—I watched the tide recede. Its exit first exposed a miasmatic black mud on each side of the ever-narrowing channel of water. Next the stench of the ooze wafted up to me. Eventually, this channel, that a few hours earlier was deep enough to allow large ocean-going vessels to pass along to the city of Bristol just upstream, was now only a few feet wide. Additionally spectacular, the terrible black river muds mysteriously transmogrified before my eyes into a lush verdant green! As the tide began to rise again, just before it would inundate a new level of mud, the green color vanished. Was this section of the river inhabited by playful leprechauns that had surfed in from the Irish Sea?

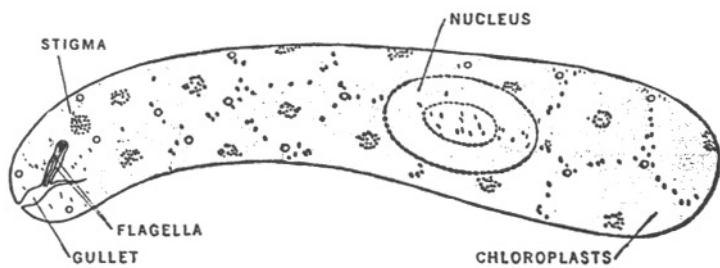
The next day I stood by river's edge under the bridge waiting for the tide to recede. Again, as it did before, the surface of the exposed mud slowly turned green. The smell was terrible, but I donned rubber hip boots and with more than a little trepidation, stepped into the newly exposed mephitic ooze. Walking was very difficult because with each step I sunk down to my knee caps, and then the suction made it almost impossible to pull my foot out without leaving the boot stuck there. I worried that I might easily lose my balance and fall face down in the disgusting river bottom.<sup>1</sup> I pressed ahead and collected some of the green-covered mud in a Petri dish and retreated back up to my car. There I found a group of locals who had come out of the Red Lion Pub to watch my der-ring-do; as if I were the paid entertainment, some of them seemed disappointed at not seeing a pratfall. But they were friendly pub regulars, and once I got my disgustingly mud-frosted boots off, and they learned that I was a "Yank," they invited me into the pub for a pint of bitter.

Thus refreshed, I returned to my lab and examined the mud under a microscope. This was a peek-and-shriek viewing: Everything in the muck was not dead and rotting as the smell certainly suggested; in fact, the opposite was true, it was teeming with life. The main inhabitant was a plant/animal called *Euglena*, an organism that consists of a single cell that can undergo photosynthesis just like other plants, also has a mouth (called a gullet) through which it ingests living things smaller than itself; it even has an eye called a stigma.

It can also locomote by worming its way through the slimy mud. All these abilities are packed into a 130 by 25 micron dollop of protoplasm (a micron is one thousandth of a millimeter).

I soon learned the daily routine of this humble organism's life. When the tide is in, the *Euglena* bury themselves in the mud where they cannot be washed away. But when the tide recedes they ascend up and out of the mud to sit on the surface for some photosynthetic sunbathing. They are so abundant on the surface they are forced to pile on top of one another and form a layer thick enough to produce a visible verdant cover that can be seen from the bridge, 248 feet overhead. As the tide slowly returns to fill the channel, just before it inundates a new level of the shoreline, the *Euglena* reburrow into their nether world, and therefore do not wash away.

Because this behavior pattern is repeated with such beat-like regularity it is described (at least by the more romantic and classically trained scientists) as a rhythm. In spite of the relatively short distance travelled, the pattern is considered a migration. However, it is not like those of birds and caribou over and across the landscape, but up and down. Thus, this *Euglena* is said to display a vertical-migration rhythm.

*Euglena obtusa*

My new finding became financially profitable for me. After memorizing the schedule of tides I would carefully collect *Euglena*-bearing mud samples in Petri dishes from locations successively farther down the river bank as the tide receded. I would then place these dishes, with the *Euglena* sitting on the mud surface, on the sidewalk outside of the Red Lion and invite interested patrons to join me in a game. I'd say to the sports among them, "All these dishes will turn black at different times. You pick any one of them you wish and I'll tell you within plus or minus five minutes when the dish's green color will disappear. If I am right, each of you who bet will owe me a pint of bitter; if I am wrong, I'll buy you a pint." It was so obvious that such a trick could not be done that most of the patrons, and even the publican, were more than willing, at first, to take advantage of the foolish yank so deranged that he seemed to enjoy wallowing in Avon mud. However, the outcome was that I essentially drank for nothing the entire year I spent on the project—I could always find someone new who would gamble on such a sure thing. Additionally, I estimate that many pints are still owed me, because English pints are 20 ounces, and my liver could not have survived that year had I fully collected my bets. When I would return home after a day's "work" my wife often mentioned that I seemed so happy, "You must really enjoy living in England."

Since I cannot bet with you readers, I'll tell you how the ruse was accomplished. But first, some background. The tide, when it returns, rises up the shore slowly. Just before it reaches a group of *Euglena*, they bury themselves. This progressive disappearance up the slope could be clearly observed when looking down from the Brunel Bridge. In my first attempt at understanding this, I hypothesized that underground water from the returning tide must actually reach the *Euglena* before the obvious front of surface water did. For example, perhaps the water was racing ahead of that front by capillarity through the interstices between the mud grains. The experiment designed to test this was an easy one: Isolate a sample of