As a parent of two young children, I find myself spending a lot of time lately in zoos, museums, and aquaria. Being a visitor is a strange experience, because I’ve been involved with these places for decades, working in museum collections and even helping to prepare exhibits on occasion. During family trips, I’ve come to realize how much my vocation can make me numb to the beauty and sublime complexity of our world and our bodies. I teach and write about millions of years of history and about bizarre ancient worlds, and usually my interest is detached and analytic. Now I’m experiencing science with my children—in the kinds of places where I discovered my love for it in the first place.

One special moment happened recently with my son at the Museum of Science and Industry in Chicago. We’ve gone there regularly over the past three years because of his love of trains and the fact that there is a huge model railroad smack in the center of the place. I’ve spent countless hours at that one exhibit tracing model locomotives on their little trek from Chicago to Seattle. After a number of weekly visits
to this shrine for the train-obsessed, Nathaniel and I walked to corners of the museum we had failed to visit during our train-watching ventures or occasional forays to the full-size tractors and planes. In the back of the museum, in the Henry Crown Space Center, model planets hang from the ceiling and space suits lie in cases together with other memorabilia of the space program of the 1960s and 1970s. I was under the presumption that in the back of the museum I would see the trivia that didn’t make it to the major exhibits up front. One display consisted of a battered space capsule that you could walk around and look inside. It didn’t look significant; it seemed way too small and jerry-rigged to be anything really important. The placard was strangely formal, and I had to read it several times before it dawned on me: here was the original Command Module from *Apollo 8*, the actual vessel that carried James Lovell, Frank Borman, and William Anders on humanity’s first trip to the moon and back. This was the spacecraft whose path I followed during Christmas break in third grade, and here I was thirty-eight years later with my own son, looking at the real thing. Of course it was battered. I could see the scars of its journey and subsequent return to earth. Nathaniel was completely disinterested, so I grabbed him and tried to explain what it was. But I couldn’t speak; my voice became so choked with emotion that I could barely utter a single word. After a few minutes, I regained my composure and told him the story of man’s trip to the moon.

But the story I can't tell him until he is older is why I
became speechless and emotional. The real story is that *Apollo 8* is a symbol for the power of science to explain and make our universe knowable. People can quibble over the extent to which the space program was about science or politics, but the central fact remains as clear today as it was in 1968: *Apollo 8* was a product of the essential optimism that fuels the best science. It exemplifies how the unknown should not be a source of suspicion, fear, or retreat to superstition, but motivation to continue asking questions and seeking answers.

Just as the space program changed the way we look at the moon, paleontology and genetics are changing the way we view ourselves. As we learn more, what once seemed distant and unattainable comes within our comprehension and our grasp. We live in an age of discovery, when science is revealing the inner workings of creatures as different as jellyfish, worms, and mice. We are now seeing the glimmer of a solution to one of the greatest mysteries of science—the genetic differences that make humans distinct from other living creatures. Couple these powerful new insights with the fact that some of the most important discoveries in paleontology—new fossils and new tools to analyze them—have come to light in the past twenty years, and we are seeing the truths of our history with ever-increasing precision. Looking back through billions of years of change, everything innovative or apparently unique in the history of life is really just old stuff that has been recycled, recombined, repurposed, or otherwise modified for new
uses. This is the story of every part of us, from our sense organs to our heads, indeed our entire body plan.

What do billions of years of history mean for our lives today? Answers to fundamental questions we face—about the inner workings of our organs and our place in nature—will come from understanding how our bodies and minds have emerged from parts common to other living creatures. I can imagine few things more beautiful or intellectually profound than finding the basis for our humanity, and remedies for many of the ills we suffer, nestled inside some of the most humble creatures that have ever lived on our planet.
I have included a mix of primary and secondary sources for those interested in pursuing the topics in the book further. For accounts that use exploratory paleontological expeditions as a vehicle to discuss major questions in biology and geology, see Mike Novacek’s *Dinosaurs of the Flaming Cliffs* (New York: Anchor, 1997), Andrew Knoll’s *Life on a Young Planet* (Princeton: Princeton University Press, 2002), and John Long’s *Swimming in Stone* (Melbourne: Freemantle Press, 2006). All balance scientific analysis with descriptions of discovery in the field.

The comparative methods that I discuss, including the methods used in our walk through the zoo, are the methods of cladistics. A superb overview is Henry Gee’s *In Search of Deep Time* (New York: Free Press, 1999). Basically, I present a version of the three-taxon statement, the starting point for cladistic comparisons. A good treatment with background sources is found in Richard Forey et al., “The Lungfish, the Coelacanth and the Cow Revisited,” in H.-P.


For the origin of tetrapods: Carl Zimmer reviewed the state of the art in the field in his highly readable and well-researched *At the Water’s Edge* (New York: Free Press, 1998). Jenny Clack has written the definitive text on the whole transition, *Gaining Ground* (Bloomington: Indiana University Press, 2002). The bible of this transition, Clack’s book will bring a novice to expert status quickly.

Everything about our past is relative, even the structure of this book. I could have called this book “Our Inner Human” and written it from a fish’s point of view. The structure of that book would have been strangely similar: a focus on the history humans and fish share in bodies, brains, and cells. As we’ve seen, all life shares a deep part of its history with other species, while another part of its history is unique.

CHAPTER TWO GETTING A GRIP

Owen was by no means the first person to see the pattern of one bone–two bones–lotsa blobs–digits. Vicq-d’Azyr in the 1600s and Geoffroy St. Hilaire (1812) also made this pattern part of their worldviews. What distinguished Owen was his concept of the archetype. This was a transcendental organization of the body, reflecting the design of the Creator. St. Hilaire was searching less for an archetypical pattern hidden in all structure than for “laws of form” that


**CHAPTER THREE HANDY GENES**

The developmental biology of limb diversity has seen a number of reviews and primary papers. For a review of the classic literature see Shubin, N., and Alberch, P. (1986) A morphogenetic approach to the origin and basic organization of the tetrapod limb, *Evolutionary Biology* 20:319–387; and Hinchliffe, J. R., and Griffiths, P., “The Predochondrogenic Patterns in Tetrapod Limb Development and


CHAPTER FOUR TEETH EVERYWHERE


CHAPTER FIVE GETTING AHEAD


CHAPTER SIX THE BEST-LAI D (BODY) PLANS

The origin of body plans has been the subject of a number of book-length treatments. For one with an exceptional scope and bibliography, go to J. Valentine, On the Origin of Phyla (Chicago: University of Chicago Press, 2004).

There have been several biographies of von Baer. A short one is Jane Oppenheimer, “Baer, Karl Ernst von,” in C. Gillespie, ed., Dictionary of Scientific Biography, vol. 1 (New York: Scribners, 1970). For more detailed treatments, see Autobiography of Dr. Karl Ernst von Baer, ed. Jane Oppenheimer (1986; originally published in German, 2nd ed., 1886). See also B. E. Raikov, Karl Ernst von Baer, 1792–1876, trans. from Russian (1968), and Ludwig Stieda, Karl Ernst von Baer, 2nd ed. (1886). All these resources have large bibliographies. See also S. Gould, Ontogeny and Phylogeny (Cambridge, Mass.: Harvard University Press,
1977), for a discussion of von Baer’s laws.


For access to the huge literature on *Hox* genes and evolution, the best starting reference is Sean Carroll’s recent book *Endless Forms Most Beautiful* (New York: Norton, 2004). A recent review and interpretation of the ways that genes allow us to understand the common ancestor of bilaterally symmetrical animals is in Erwin, D., and Davidson, E. H. (2002) The last common bilaterian ancestor, *Development* 129:3021–3032.

from acorn worms does not easily fit this model, and suggests that in some taxa the map between gene activity and axis specification may have evolved. For this work, see Lowe, C. J., et al. (2006) Dorsoventral patterning in hemichordates: insights into early chordate evolution, *PLoS Biology* online access: http://dx.doi.org/journal.0040291.

CHAPTER SEVEN ADVENTURES IN BODYBUILDING


The story behind the Ediacarian animals is covered, with references, in Richard Fortey’s *Life: A Natural History of the First Four Billion Years of Life on Earth* (New York: Knopf, 1998), and Andrew Knoll’s *Life on a Young Planet* (Princeton: Princeton University Press, 2002).

CHAPTER EIGHT MAKING SCENTS

The University of Utah has an effective website, Learn. Genetics, that provides a wonderfully simple kitchen protocol for extracting DNA. The URL is http://learn.genetics.utah.edu/units/activities/extraction/


CHAPTER TEN EARS


The origin of the mammalian middle ear is discussed from the perspective of a scientific historian in P. Bowler, *Life’s Spendid Journey* (Chicago: University of Chicago Press, 1996). Key primary sources include: Reichert, C. (1837) Über die Visceralbogen der Wirbeltiere im allgemeinen und
deren Metamorphosen bei den Vogeln und Saugetieren, 


The evolutionary origin of *Pax* 2 and *Pax* 6 and the evolutionary link of ears and eyes to box jellyfish is discussed in Piatigorsky, J., and Kozmik, Z. (2004) Cubozoan jellyfish: an evo/devo model for eyes and other sensory


CHAPTER ELEVEN THE MEANING OF IT ALL

The methods of phylogenetic systematics are discussed in a number of sources. Key primary literature includes the classic work of Willi Hennig, published originally in German (*Grundzüge einer Theorie der phylogenetischen Systematik* [Berlin: Deutscher Zentralverlag, 1950]) and translated into English more than a decade later (*Phylogenetic Systematics*, trans. D. D. Davis and R. Zangerl [Urbana: University of Illinois Press, 1966]).


A comprehensive treatment of the phenomenon of independent evolution of similar features is in M. Sanderson and L. Hufford, *Homoplasy: The Recurrence of...

To see the tree of life and the different hypotheses for the relationships between living creatures, visit http://tolweb.org/tree/.


A number of websites and blogs carry accurate information and are updated frequently.

http://www.ucmp.berkeley.edu/ Produced by the Museum of Paleontology at the University of California–Berkeley, this is one of the best online resources on paleontology and evolution. It is continuously updated and revised.

http://www.scienceblogs.com/loom/ This is Carl Zimmer’s blog, a well-written, timely, and thoughtful source of information and discussion on evolution.

http://www.scienceblogs.com/pharyngula/ P. Z. Myers, a professor of developmental biology, writes this accessible, informative, and cutting-edge blog. This is a rich source of information, well worth following.

Both Zimmer’s and Myers’s blogs are at http://www.scienceblogs.com, a site that contains a number of excellent blogs also worth following for information and commentary on recent discoveries. Blogs relevant to the theme of this book at that site include Afarensis, Tetrapod Zoology, Evolving Thoughts, and Gene Expression.

http://www.tolweb.org/tree/ The Tree of Life Project provides a regularly updated and authoritative treatment of the relationships among all groups of life. Like the UCMP
page at Berkeley, it also includes resources for learning about how evolutionary trees are made and interpreted.
ACKNOWLEDGMENTS

All the illustrations, except where noted, are by Ms. Kalliopi Monoyios (www.kalliopimonoyios.com). Kapi read drafts of the manuscript and not only improved the text but designed art that matched it. I have been truly fortunate to work with someone with so many talents. Scott Rawlins (Arcadia University) generously gave permission to use his elegant rendering of *Sauripterus* in Chapter 2. Ted Daeschler (Academy of Natural Sciences of Philadelphia) graciously provided his superb photos of the great *Tiktaalik* “C” specimen. Thanks are due to Phillip Donoghue (University of Bristol) and Mark Purnell (University of Leicester) for permission to use their rendering of the conodont tooth array, McGraw-Hill for permission to use the textbook figure that started the hunt for *Tiktaalik*, and Steven Campana of the Canadian Shark Research Laboratory for the photos of shark organs.

One of the greatest debts students of anatomy have is to the people who donate their bodies so that we can learn. It is a rare privilege to learn from a real body. Sitting through long hours in the lab, one feels a very profound connection
to the donors who make the experience possible. I felt that connection again while writing this book.

The ideas I present here are rooted in research I’ve done and in classes I’ve taught. Colleagues and students too numerous to name—undergraduates, medical students, and graduate students—have played a role in the thinking that went into these pages.

I owe a great debt to the colleagues I have worked with over the years. Ted Daeschler, Farish A. Jenkins, Jr., Fred Mullison, Paul Olsen, William Amaral, Jason Downs, and Chuck Schaff have all been part of the stories I tell here. Without these people I would have had no reservoir of experience on which to draw, nor would I have had as much fun along the way. Members of my laboratory at the University of Chicago—Randall Dahn, Marcus Davis, Adam Franssen, Andrew Gillis, Christian Kammerer, Kalliopi Monoyios, and Becky Shearman—all influenced my thinking and tolerated my time away from the bench as I wrote.

Colleagues who gave their time to provide needed background or comments on the manuscript include Kamla Ahluwalia, Sean Carroll, Michael Coates, Randall Dahn, Marcus Davis, Anna DiRienzo, Andrew Gillis, Lance Grande, Elizabeth Grove, Nicholas Hatsopoulos, Robert Ho, Betty Katsaros, Michael LaBarbera, Chris Lowe, Daniel Margoliash, Kalliopi Monoyios, Jonathan Pritchard, Vicky Prince, Cliff Ragsdale, Nino Ramirez, Callum Ross, Avi Stopper, Cliff Tabin, and John Zeller. Haytham Abu-Zayd helped with many administrative matters. My own teachers
of anatomy in the Harvard–MIT Health Sciences and Technology program, Farish A. Jenkins, Jr., and Lee Gehrke, stimulated an interest that has lasted over twenty years.

Key advice at the inception of the project, and inspiration throughout, came from Sean Carroll and Carl Zimmer.

The Wellfleet Public Library (Wellfleet, Massachusetts) provided a comfortable home, and much-needed retreat, where I wrote significant parts of the book. A brief stint at the American Academy in Berlin put me in an environment that proved critical when I was completing the manuscript.

My two bosses, Dr. James Madara, M.D. (CEO, University of Chicago Medical Center, Vice President for Medical Affairs, Dean and Sara and Harold Thompson Distinguished Service Professor in the Biological Sciences Division and the Pritzker School of Medicine), and John McCarter, Jr. (CEO, The Field Museum), supported this project and the research behind it. It has been a true pleasure to work with such insightful and compassionate leaders.

I have been fortunate to teach at the University of Chicago and to have had the opportunity to interact with the leadership of the Pritzker School of Medicine there. The deans, Holly Humphrey and Halina Bruckner, graciously welcomed a paleontologist to their team. Through interacting with them I came to appreciate the challenges and importance of basic medical education.

It has been a great pleasure to be associated with The Field Museum in Chicago, where I have had the opportunity to work with a unique group of people dedicated to
scientific discovery, application, and outreach. These colleagues include Elizabeth Babcock, Joseph Brennan, Sheila Cawley, Jim Croft, Lance Grande, Melissa Hilton, Ed Horner, Debra Moskovits, Laura Sadler, Sean VanDerziel, and Diane White. I am also grateful for the support, guidance, and encouragement I have received from the leaders of the Committee on Science of the Board of Trustees at The Field Museum, James L. Alexander and Adele S. Simmons.

I am indebted to my agent, Katinka Matson, for helping me turn an idea into a proposal and for advice throughout the process. I feel privileged to have worked with Marty Asher, my editor. Like a patient teacher, he gave me a nurturing combination of advice, time, and encouragement to help me find my way. Zachary Wagman contributed to this project in countless ways by being free with his time, keen editorial eye, and good counsel. Dan Frank made insightful suggestions that stimulated me to think about the story in new ways. Jolanta Benal copyedited the text and improved the presentation immeasurably. I am very grateful to Ellen Feldman, Kristen Bearse, and the production team for their hard work under a tight schedule.

My parents, Gloria and Seymour Shubin, always knew that I would write a book, even before I did. Without their faith in me, I doubt that I ever would have put a word on paper.

My wife, Michele Seidl, and our children, Nathaniel and Hannah, have been living with fish—both *Tiktaalik* and this
book—for the better part of two years. Michele read and commented on every draft of this text and supported long weekend absences while I wrote. Her patience and love made it all possible.