THE ART OF CHANGING THE BRAIN
ENRICHING THE PRACTICE OF TEACHING BY EXPLORING THE BIOLOGY OF LEARNING

JAMES E. ZULL
‘The Art of Changing the Brain’ is teaching. Zull argues that educators can use knowledge about the brain to enhance pedagogical techniques. He does an excellent job of demonstrating his thesis by describing good approaches: e.g., increasing reception of information by enhancing the sensory aspects of teaching materials; taking advantage of integrative mechanisms by allowing time for reflection; maximizing the adaptive functions of the brain by challenging students to be creative; using action areas of the brain by providing activities to confirm and extend learning. Teachers need to recognize that motivational-emotional systems of the brain modulate cognitive functions and that pedagogies [that] attempt to force students to learn in ways that violate brain mechanisms are likely to be counterproductive. Zull’s years of experience as both professor of biology and director of a university teaching institute are apparent; the book is well written and appropriately technical for the audience interested in applying current knowledge about the brain to learning and instructing. Highly recommended.”

—Choice

“Writing for all educators, [Zull’s] theme is that a better understanding of brain function will promote a more flexible and varied approach to learning. The results offer a refreshing clarity. [In] his fine book . . . Zull has done a remarkable job of simplifying both brain function and learning processes. It is a synthesis of what we know about the brain and about learning, a synthesis that simplifies both fields to draw a usable map of the terrain of learning. I encourage educators at all levels to grapple with Zull’s model . . . and integrate his insights with their own experience and understanding of the learning process. A work like The Art of Changing the Brain has long been needed.”

—Pierce J. Howard,
Cerebellum

“This is the best book I have read about the brain and learning. Zull takes us on a fascinating and vivid tour of the brain, revealing the intricate structure of the organ designed by evolution to learn from experience. Using wonderful stories from his own experience, filled with insight, humor, and occasional twinges of pain, this wise and humane educator and scientist describes his concept that teaching is the art of changing the brain. His perspective forms the foundation for a teaching approach that can dramatically improve human learning.”

—David A. Kolb,
Department of Organizational Behavior, Case Western Reserve University
“I found The Art of Changing the Brain to be deeply thought provoking. It is not only grounded in emerging brain research but relates such research directly to the experiences of students and the challenges of classroom teaching. As a middle school administrator, I believe that this book will become an excellent and unique resource for the ongoing professional growth of educators. The book can be profitably read by any teacher at any level, and I intend to use it in my own courses for students in education classes.”

—Robert Brownlee,
Curriculum Specialist at Kirk Middle School, East Cleveland

“I have just discovered your amazing book. I find I reread, and make so many connections as I go, and I do not wish to rush!”

—Martha M. Decker,
Assistant Professor of Education, Morehead State University, Kentucky

“I read (devoured) this book three times, and I am overwhelmed by it. It is just perfectly and brilliantly thought through! The reader receives important information in small and easily digestible portions. The illustrations from the author’s own teaching experience underscore the points he makes in a profound way.”

—Margaret Arnold,
Education Graduate Student, Harvard Graduate School of Education, and Augsburg University
THE ART OF CHANGING THE BRAIN
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Enriching Teaching by Exploring the Biology of Learning

James E. Zull
To my mother, Eileen Gates, who showed me the joy of learning—and living—throughout my life

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Who Should Read This Book?

My hope is that all educators will find value in this book. Whether you teach children, teens, or adults, you can only gain by reading and thinking about the brain. I have written for an audience at all levels of education.

But do not set this book aside just because you don’t make your living by teaching. You are still a teacher!

Our daily lives require us all to teach. We must be understood by other people: our students, our children, our employees, our parents, our friends, and our enemies. Whether learning to read, doing a job, or just conversing with others, we want and need to help people learn. Life is learning; life is teaching. And the more you understand the brain, the more artful you can be when you must teach!
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Some critics warned me that this book could not be written, or should not. And it didn’t take long for me to discover good reasons for these warnings. The opportunities to make mistakes are unending. And I am sure I have taken advantage of a large number of them, despite striving to avoid doing so.

I apologize for these inevitable, but presently undetected, errors of content and interpretation. However, there would be many more were it not for the support of many dear and honest friends and critics.

Beginning with my colleagues at Case Western Reserve, I must first thank David and Alice Kolb. It was David’s work and profound insights on human learning that triggered the very conception of the book. Once Alice showed up on the scene, she gave me such encouragement that my periodic instincts to abort were forgotten. I also thank Mano Singham, who is wiser about teaching than anyone I know and who cheerfully and analytically helped me keep my message on target for teachers. Lyn Turkstra read every chapter and covered the pages with comments as she gently but firmly guided me around the territory of the brain. In addition, Hillel Chiel, Alison Hall, David Katz, and Peter Whitehouse all added to my knowledge of the brain.

I am also indebted to my friends and colleagues in the Mind, Brain, and Education Program at the Harvard Graduate School of Education. Their support, insightful criticism, and personal engagement extended far beyond what I had any right to expect. I especially thank Kurt Fischer and Howard Gardner who both encouraged me at crucial times during my brief sabbatical at Harvard. I also got valuable insights from Marc Schwartz through his work on science education for middle school children. First among the students at Harvard is Juliana Paré-Bagolev, who read most chapters and gave many hours of her time, all the while continuing her own teaching and brain-imaging research on
dyslexia and bringing a new child into the world. Other students who gave me valuable feedback are Mary Helen Immordino-Yang, whose comments prompted me to completely rewrite chapter 1, and Mike Connell, whose observations on certain chapters led to important changes and additions.

Kathy Schuh at the University of Iowa also critiqued parts of the book, and her comments deepened my understanding. I also am grateful to Neil Fleming, my New Zealand partner in thinking about teaching. His decades of accumulated wisdom proved invaluable in helping me clarify confusing places in the book, and the extensive and detailed critiques he produced represented an expenditure of time and effort that both surprised and humbled me.

My publisher, John von Knorring, first encouraged me to write a book on education and the brain and then stuck with me through several abortive efforts, in which I did not respect the task enough. When I finally began to make progress, he was first in line encouraging me and urging me on to publication. For all this and for his ability to distinguish good from bad, I am grateful. I also thank Larry Goldberg, my editor, and his team at Shepherd Incorporated, for their personal interest and careful work. It always seemed that this project was more than just a job to them.

I find myself groping for the right words to thank my family. I am amazed at their patience when I forgot important engagements and other responsibilities, while totally engrossed in writing or, worse, dreaming. I especially thank my wife, Susan, for the weekends sacrificed and the innumerable blank stares tolerated as I, lost in my theories, failed to hold up my end of the conversation. I never felt more support, and sometimes never more selfish, as she allowed me, indeed encouraged me, to pursue my ideas. This generosity and love continually reminded me that, no matter how it may have seemed at critical moments, in the end she is the best idea I ever pursued.
Learning is about biology. This obvious fact has been lurking just beneath our consciousness for a long time. It is why teachers felt excited as neuroscience blossomed in the past few decades. And it is why some predicted a revolution in education, once we found out how the brain works.

But as science gave us more information, teachers began to realize that this did not automatically produce better education. Neuroscientists could not tell us how to teach. In fact, biologists still pay little attention to our concerns. They are excited about science, not about education.

This means that, to a great extent, educators have been left to interpret neuroscience on their own. There is virtually nothing on this topic written by scientists, which is one reason I decided to write this book. There was a gap waiting to be filled.

But revolution is not my goal. There is no reason to abandon the good practices that cognitive science and education research have given us. Rather, I hope to deepen and enrich our understanding of these practices. Biology can enrich what we already do.

This enrichment comes, to a great extent, from the perspective that biology provides for the teacher. Often, our perspective of teaching is from above. We view the learner as needing our help, which we hand down to him. From this perspective we can forget that the actual learning takes place down there in the brain and body of the learner. When we turn this around and begin to ask about the learning itself, we may see things differently. We may see both ourselves and our students as the biological creatures we are, and this more grounded perspective is what ultimately enriches us.
Let me briefly explain some challenges the book presented, and how I tried to deal with them.

When my friends first heard the title of my book, some of them reacted strongly. One remarked that her first thought was of “mind control.” Another said, “It sounds aggressive! Are we really going after their brains?”

Although these comments seemed a little extreme, they did give me pause. I even considered changing the title. But I couldn’t bear the thought that you might look at my book, there on the shelf, read the title, and completely miss the main message.

This main message is that learning is change. It is change in ourselves, because it is change in the brain. Thus the art of teaching must be the art of changing the brain. At least this much should be up front.

Another struggle was the question of defining learning. I was advised that I must tell the reader what I mean by learning. Someplace in the book I must give my definition. But I have not done so. Or, at least, you will not find a particular place in the book where I focus on a definition.

I had two reasons for this decision. First, I came to feel that inventing a definition would make more trouble than it was worth. Such definitions, in themselves, can need explaining, and the last thing I needed was to sow further confusion or add to the explaining.

Second, one of my goals is for you to find your own definition of learning. Learning is about change, and it is change. It is a living, growing thing that comes through different routes and leads to different ends as our lives evolve and grow. I cannot even say that I have yet defined it, but I am developing a definition. And I am content for you to feel the same. If you find your own definition changing as you read, you will understand the life in learning, and you may want to put off constructing your own definition, at least for a while.

When they looked at my manuscript, my friends in the learning and education field sometimes wanted to define me. This became another struggle. Am I a constructivist, an associationist, or a traditionalist? Where do my allies lie in the learning debates, if I have any?

If you are inclined to ask that question, let me suggest that you read more than one or two chapters before you decide. I am not sure where
INTRODUCTION

I fit, and it could be that I am simply a misfit. I say this because my starting point is always biology. I just go where biology leads me. Sometimes what I see is rather traditional, and sometimes it is far out on the wings of constructivism. Or it might be something quite different from either. But I don’t care, as long as I believe I have been faithful to the biology. In the end, I am a biologist.

This question of defining things also is apparent in the way I speak of “brain science” or “brain research.” You will find that I jump around a lot between cognitive science, cognitive neuroscience, and neuroscience without paying much attention to the terms at all. I have just been sloppy about this.

There is a reason for this sloppiness. I have come to distrust the definitions of disciplines that we invent as our knowledge grows. These definitions are useful for the experts but can be confusing to others. And they may imply divisions and differences that don’t really exist. Even experts get caught up in this, sometimes arguing fiercely that something is really “cognitive” rather than “neuronal.”

The teachers who read my manuscript sometimes wanted more specifics. Exactly what should teachers do in order to “change the brain”? My instinct was to shy away from making suggestions, but I didn’t always follow that instinct. So you will find some specific ideas, especially in chapters 6 and 7, and I frequently mention things that I have tried or would like to try. But I still don’t have a lot of faith in giving directions to teachers. In fact, I have often noticed that when teachers start telling other teachers how to solve their problems, things can quickly get tense. For the most part, we seem to want to solve our own problems, and I am happy to leave it that way.

I also struggled to keep the book at a reasonable length. This sometimes meant that I could only mention a topic or idea that really deserved much more attention. I often felt frustrated with what I wasn’t saying! I tried to rectify this with endnotes, which occasionally became quite lengthy, or by referencing a specific article where the science details can be found. So if you find yourself frustrated or impatient with something, it is possible that you may find what you need, or part of what you need, in these notes.

Finally, I am particularly sensitive to the reactions of my biology and neuroscience colleagues. You may feel that my biological generalizations...
are inadequate or even misleading. I only touch the surface of our knowledge about nervous systems. This is necessary, and I have worked hard to be accurate, but if you still cannot forgive me, at least you should know that I am fully aware of this shortcoming.

* * *

Let me end this introduction by telling you about a hope. When I first started, I wanted the book to be brilliant. I was sure that my ideas were unique and important. But along the way, I have been rightly humbled. This subject is majestic and my brain isn’t.

But it wasn’t humility that led me to change my hopes: it was my recognition of a bigger goal. It came to me when, after one of my workshops, a teacher came up to me and said, “I am going to change how I teach. This was so useful!”

What a rush! Someone found my ideas useful. And I realized that, in the end, this is what matters the most. The greatest testament is to have my ideas applied: to have been useful.
WHAT WE ALREADY KNOW

TO BEGIN, FIND OUT ABOUT EXISTING NEURON NETWORKS

The single most important factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.

—David Ausubel

A group of professors sat around the large oak table in our conference room, eating pizza and talking. These “teaching conversations” were surprisingly successful. Our teachers seemed to need times like this when they could talk about their successes and their worries.

At one end of the table sat Thom, a frail-looking physics professor. He was a regular, and we could always count on him for clear insights and comments, delivered in his clipped British accent. We deeply respected Thom’s intellect; he made us think—and usually laugh.

But today he was not in a laughing mood. We understood that when he suddenly grabbed a handful of papers and, Frisbee-like, flung them across the table.

“These students can’t grasp even simple ideas!” he clipped. “Like those papers! I bet you all know that they would keep moving forever in the absence of any resistance! But my students just don’t get it! Conservation of momentum is as foreign to them as Chinese!”

I happened to be sitting at the other end of the table, and Thom’s papers stopped right in front of me. I, too, noted that they did not
continue on their path forever. But I did know what he meant. If there were no resistance from the air in the room, no friction with the table, and no other resistance anywhere, they would indeed still be sailing along.

I gathered up the papers, thinking what I could say. As nominal leader of the discussion, I should respond somehow. But I found myself at a loss. In fact, it wasn’t until later, while driving home from work that it came to me.

“I know what I should have told Thom!” I thought. “I hope I can see him tomorrow. We’ll have to talk about neuronal networks!”

* * *

Part I laid a foundation for learning. Now I will try to build on this foundation and develop some specific ideas about helping people learn.

This will require us to look deeper into the structure of the brain to examine the stuff of the brain itself, as it appears through a microscope. What we will see is that the brain is made up of complicated cells connected to one another in an immense network of fibers and branches. The cells are called neurons, and the connections create neuronal networks.

As amazing as these networks are physically, what they represent is even more amazing. In some ways we could say that when we look at pictures of neuronal networks of a human brain, we see a tiny bit of the knowledge the brain once had in its physical form. Neuronal networks are knowledge.

Prior Knowledge

What do I mean when I say “neuronal networks are knowledge”? How can physical structures created by linkage of cells in the brain be equated to knowledge?

You might think this means knowledge is stored in neuronal networks. That is true, but it is incomplete. Not only is knowledge stored in the brain, it is produced by the brain through formation and change in neuronal networks. Any change in knowledge must come from some change in neuronal networks.

Although he may not have realized it, Ausubel made a profound biological statement when he staked out prior knowledge as the begin-
ning of teaching in the quote at the beginning of this chapter. The biological equivalent of his assertion is:

The single most important factor in learning is the existing networks of neurons in the learner’s brain.Ascertain what they are and teach accordingly.

This does not imply that teachers can look into brains and see neuronal networks, but rather that when we find out what our students already know, we are actually finding out about their neuronal networks. We are discovering the connections they have in their brains.

I will develop three important ideas about prior knowledge in what follows. First, prior knowledge is a fact. All learners, even newborn babies, have some prior knowledge. Learners do not begin with a blank slate. Second, prior knowledge is persistent. The connections in these physical networks of neurons are strong. They do not vanish with a dismissive comment by a teacher or a red mark on a paper. Third, prior knowledge is the beginning of new knowledge. It is always where all learners start. They have no choice.

Thom’s Students

It should be apparent by now why I thought I should tell Thom about neuronal networks. It seemed that the student brains in Thom’s class simply were not prepared for what he wanted them to learn. The things they already knew and understood just weren’t doing the trick. They didn’t have the right neuronal networks.

It also seemed that Thom might not have considered the idea of prior knowledge, or if he had, he was suspicious of it. That would not be a surprise. Science teachers especially are leery of what students already believe about the physical world and about physics. For example, students may think that heavier objects fall faster than light ones—despite Galileo. They may believe that only moving things generate force, or they may be convinced that jackets have warmth. Their experience has led them to beliefs like this, and those beliefs can be firmly fixed.

Thom might well have felt that he should stay as far away as possible from the prior knowledge of his students.
An Inescapable Fact

The problem for Thom is that he doesn’t have a choice. No one can understand anything if it isn’t connected in some way to something they already know. Let me illustrate this.

Imagine you land on a desert island and there you find one other person. This person uses a different language and comes from a different culture. Can you communicate? Sure! But how do you do it? You find something that you both understand. It could be a gesture, a wag of your index finger that says “Come here!” It could be a laugh or a sob. But whatever it is, you must find some prior knowledge that you share.

We could think of Thom and his students the same way. His students all have their own personal prior knowledge about conservation of momentum. They have their own beliefs about what “conservation” means and what “momentum” means. They have their own experiences with moving objects and with things that resist movement or reduce it. Whatever their experience, that is where they start.

If Thom is to communicate with these strangers in the land of physics, he must find some prior knowledge he shares with them.

Neurons

When we speak of prior knowledge, we are speaking of something physical. It builds as brains physically change, and it is held in place by physical connections. We could say that prior knowledge is a thing!

That probably sounds strange. We aren’t used to taking these concepts of learning and knowing so literally. But I found that this literal way of thinking was an important step toward understanding how to help people learn. It made me realize that I could not banish wrong ideas simply by stating that they were wrong. This was the beginning of a great change in my teaching methods.

But I don’t expect that you will just take my claims on faith. They will have no meaning if you do. These suggestions will just be something that you remember rather than something you understand. You will not have a story that connects with the idea, so your emotional brain will not be involved.
We need the story that lies behind all this. And to tell that story we must begin with the characters in it—the neurons.

Neurons are cells. That may not be obvious when we first look them. Generally, they are small, like almost all cells, but as the illustration below shows, they can look more like a bush in your front yard, or a leafless tree in an Ohio winter, than a cell.

It is all the branches that make neurons look so strange. And the branches can make the cell look quite large, as is the case for the neuron at the bottom. The arrows in the illustration point out that there are actually two different kinds of branches. One branch usually looks somewhat different from the others, if we look closely.
You will notice that the arrows point to a single branch that looks longer and more lonely than the others. These branches are called axons. The rest of the branches are called dendrites. In general, the dendrites determine how a neuron looks. These dendrites and the axon branch from a cell body (see next drawing).

This is what our characters look like. What do they do? What is their behavior?

Neurons are sensitive and observant. They pick up signals and send them to other neurons. These signals can come from the outside world in the form of light or sound, for example, or from other neurons. In general, the dendrites pick up the signals and send them toward the center of the cell, the cell body.

Axons, on the other hand, collect the signals coming in from the dendrites and send them together away from the cell body. This process goes on to some extent all the time, and a certain background of this signaling happens randomly.

The last thing we need to know about neurons for our immediate purposes is that they make friends easily. They form connections with other neurons. The axons end by coming up against the dendrites or even the cell body of other neurons. The signals then leap from the axon to the next cell, and if there are enough of these signals, they are carried on in the same way by the second neuron. This place where the signals pass from one neuron to another is known as a synapse.

All of this is very difficult to see in actual pictures of neurons, but the drawing below puts it together in a diagrammatic way. The only things in this drawing I haven’t mentioned so far are the bands of material around the axon of the cell on the left. This axon coating is called myelin, and it allows the signals to pass much more quickly along the axons, basically jumping from node to node in the myelin covering. When we are first born, many axons in our brain do not have myelin coats, and many never have any. But other axons develop their myelin coating at different times in the development of the brain, and this is an important part of the natural growth in brain abilities and skills.
Neuronal Networks of the Brain

The picture I just described shows a network of four neurons, and it illustrates what I mean when I speak of neuronal networks. You could add in a number of new neurons to this drawing and form a more extended network. In fact, using just this simple drawing your network could get pretty complicated pretty fast! If you count, you will identify nearly 30 unused dendrites in these four neurons; making a single contact with each of them would create quite a tangle of connections.

But that is nothing. When we come to the brain and the actual neuronal networks found there, the numbers of connections, and the tangle of neurons, is truly incomprehensible.

A human brain has about 100 billion neurons (eleven zeros). And estimates range as high as 10,000 connections per neuron. That comes to a total of a thousand trillion connections (that’s fifteen zeros) in an average human brain. There are ten to a hundred times more connections in our brain than there are cells in our body.

It is really impossible to visualize all these connections, even in a small piece of the brain. But we can get some idea of their extent by looking at the potential sites for synapse formation on a single neuron. This is shown in the following drawing, which depicts a small segment of the dendritic branches from an isolated hippocampal neuron. Sites that could form synapses are identified by dots. These sites are not
actual synapses, but they could become synapses if this neuron were back in its home in the hippocampus, and the neuronal networks grew more and more complex through learning and remembering.

A final point is that no matter how many synapses a particular neuron has, it also seems to have the potential to grow more. We will talk about this in chapter 7, when we look at how neuronal networks change.

**Neuronal Networks Are Prior Knowledge**

I have said that prior knowledge is a thing. Now you can see what that claim means. There is a neuronal network in our brain for everything we know.

Let’s look at an example. Each of us knows our name. We recognize it, we know how to say it, and we know how to write it. This is part of our existing knowledge. Our ability to recognize our name comes from neuronal networks in our sensory brain. When Jane sees “Jane” written on the blackboard, a group of neurons in her visual cor-
tex that are triggered by the shapes of the letters in her name always fire together. The visual stimulus, Jane’s name in writing, triggers the same neuronal network every time. To her brain, the name Jane is a neuronal network.

We can go on. Jane has written her name so often that she does it without thinking. A neuronal network in her memory brain is connected to another one in her motor brain, and she writes Jane without a thought. The motor network for writing Jane is unique; it is her knowledge of how to write her name. And when she signs her checks, Jane uses the larger neuronal network, which consists of a combination of her memory network for her name and her motor brain, which generates the movements of her hand and arm as she writes.

It seems that every fact we know, every idea we understand, and every action we take has the form of a network of neurons in our brain. We know of no other form.

The Divided/Connected Brain

The brain is constructed so that small parts of knowledge are located in small groups of neurons connected to each other in small networks. These small networks are connected with other small networks to produce larger ones, and there does not seem to be any particular limit to these connections. Thus, complex experiences or ideas consist of extensive networks. The brain is a structure that at once is almost infinitely divided and infinitely connected.

These small parts of knowledge are such things as straight lines versus slanted lines, the vibrations produced by playing a single musical note versus another note, or a geometric form such as a cube versus a circle. The small networks are made up of neurons close to one another, and almost every day research brings new information about specific brain functions localized to a particular small part of the brain. We know that there are certain areas for hearing, for creating language, for working memory, for long-term memory, for creating images, for understanding nouns, for understanding verbs, for doing arithmetic, for doing geometry, for recognizing perfect pitch, for remembering the Beatles’ Yellow Submarine, and for recalling the first bars of Beethoven’s Fifth Symphony.
Specific groups of neurons fire when we hear middle C on the piano, but different groups fire when we hear C sharp. Specific groups of neurons fire when we see red, but a different specific group fires when we see blue. Different groups of neurons fire when we feel happy, angry, sad, or afraid. Certain neurons fire when we are in love, and others when it’s just lust.

Name anything that humans can know, think, feel, or do, and we can find a part of the brain, or a combination of parts, that specializes in that thing. But at the same time, combinations of these neuron groups can also fire at the same time. The more complex the task, the more parts of the brain that are needed, and the larger the neuronal network that comes into play. It is not a stretch to say that any neuronal network might potentially become connected with any other network, if that connection is a useful one. For example, the network that triggers Yellow Submarine can become connected with the network for the name “Jane,” if Jane continually hums that tune.

Thus, in cognitive tasks many different parts of the brain can be involved at once. At some complex points in our lives—moments that may try our minds and hearts (i.e., the cognitive and emotional parts of our brains)—large amounts of our brain may be active at once in neuronal networks of incomprehensible complexity.

Progress Report from Thom

Thom and I were eating lunch. We had talked about these ideas for a few days, but he hadn’t said anything about teaching. I couldn’t stand it any longer.

“Well?” I said. “What do you think? Can you use any of this in your class?”

He looked at me in that penetrating and quizzical way of his. “I hate to give you the satisfaction,” he said. “But you’re right about one thing. I hadn’t thought of my teaching that way. If what students believe is a physical thing, physical connections between real neurons, it sounds more compelling. It might be harder to teach some things than I thought.”

“What do you mean?” I asked.

“Well, I just assume that when I explain things in words, or equations, or graphs, they will get the idea. But if those words or graphs
have to match up with physical networks in their brains, there’s a lot of room for mismatches. Even one word, or a small part of my drawing, could do it. The student could hit a brick wall right then!”

“That can happen,” I agreed.

“And what if I try to correct a mistake, or a wrong idea?” Thom clipped ahead quickly. “How can what I say actually change a physical set of connections in someone’s brain?”

“It’s not easy,” I said. “I guess we’re learning that from your students.”

“Well, it might help if I knew what networks they already have,” he pondered. “At least that would give me some clues. I might be able to build on that.”

He paused, thinking hard. “Or maybe there’s another angle. If I could find out when they aren’t getting it, when they stumble into a brick wall, at least I would know what networks they don’t have.”

Thom laughed. “Well, one network they don’t have for sure is the one for conservation of momentum. We know that much!”

After a quiet moment, Thom asked, “What’s known about how these neuronal connections get created in the first place? Can’t I make any generalizations? Can’t I assume that there are some connections they all have?”

This startled me a little. His quick mind had moved ahead of me. I was still thinking about how something could move forever. Did I have that neuronal network in my own brain?

Neuronal Networks Are the Beginning

Thom had understood one thing very well. Whatever the neuronal networks are in the student brain, a teacher cannot remove them. They are a physical fact. As we will see later, it may be possible to reduce the use of particular networks, or to use other networks in their place, and some networks may die out or weaken with disuse. But no teacher, with a wave of the hand, a red pen, or even with a cogent and crystal-clear explanation, can remove an existing neuronal network from a student’s brain.

The useful approach for a teacher is to find ways to build on existing neuronal networks. Starting with whatever our students already
know and building from there is a biologically based idea for pedagogy. It suggests that we should find out what students believe, and far from disparaging it or trying to ignore it, use it as a tool for teaching. Existing neuronal networks open the door to effective teaching.

Thom’s last question then, in an excellent one. Are there common sets of neuronal networks that we can begin with? Can we assume anything about what students already know?

One thing we can be sure of is that the neuronal networks in student brains are related to their own life experience. The things they have seen, heard, touched, smelled and tasted are what connects for them. And things they have tried to do or have succeeded in doing will also be there. There are neuronal networks for the facts of their own lives.

So Thom can generalize, at least a little. He can assume that most of his students will understand when he speaks of things they have all experienced. The objects in their worlds, the language they share, the music, the shapes, textures, smells, and tastes will all be there. Certainly there will be differences, things sensed by one brain but not by another, but this generalization gives us a starting point.

**The Importance of the Concrete**

As we will see in chapter 8, our brains make physical maps of the world, and the existing neuronal networks are replicas of the physical form of objects in the world, those objects and events that make up our concrete experience. For example, light reflected off an object such as a house or tree comes into our eyes in the same geometric arrangement for us all. (See chapter 8.) The eyes then send that information to the same parts of our visual brains, and the way it is recorded there is a physical reflection of the object itself. So the neuronal networks formed when we sense the outside world are most likely to be similar in each of us; they are created from the same source—the physical world.

How we interpret them, or perceive them, is another matter. Eventually, as we proceed with this book, we may well come to think that almost every brain makes a somewhat different meaning from the same concrete facts. Our perceptions and meanings come from the influence
of neuronal networks in other, nonsensory parts of the brain. So, we can’t assume anything about meaning.

Despite this personal modification of sensory experience into perceptions, it still seems that a teacher’s best chance is to begin with concrete examples. The abstract and theoretical have less meaning if no neuronal networks are associated with the concrete experience of the learner. For example, medical education might start with patients, and arithmetic might start with purchases at the store. Likewise, an understanding of genetics might start with a learner’s family traits, economics with the cost of CDs, and civil engineering with concrete examples of interstate highways (pun intended).

These suggestions are really just another way to reaffirm Ausubel’s claim. “What we already know” is concrete to us. Our knowledge of it makes it real, part of our experience.

However, especially in higher education, teachers do not necessarily start with the concrete. Our deeper understanding of our fields can lead us to start with principles rather than examples. We may think we should provide students with the “tools” for solving problems before we show them the problems. Or, we may start with the atom rather than the object, the equation rather than the phenomenon, the concept of supply and demand rather than economic stories. We start where we are, not where they are.

Beyond the Facts—Neuronal Networks for Ideas

But Thom wants his students to understand an abstract concept, something they never have, and never will, actually experience. What do our ideas of neuronal networks tell us about that challenge?

My suggestion is that abstract concepts are always embedded in concrete experience. For example, observing or riding in automobiles is a concrete experience but that experience is associated with concepts of speed and acceleration. At an even more basic level, the world gives us many examples of multiplicity in objects: cars, apples, people. This concrete information inherently contains abstract ideas of numbers, arithmetic, and statistics.

It’s possible that all our brains become comfortable with certain abstract ideas through our real experiences. We may not recognize the
abstractions or have names for them, but I suspect they are there. If we accept the proposition that our physical brain is the whole story (which you know is my bias), then it must be true that there are neuronal networks for all the ideas that allow us to understand ourselves and the world—ideas like time, shape, novelty, number, causation, extent, qualities, self/other, mass, and hardness. All these come from the world of the concrete.8

I propose, then, that Thom’s students already have some neuronal networks on which Thom can build. They may not know it, because they have never connected them with the word momentum. But they probably know that heavy things are harder to stop than lighter things, and they do know that fast-moving objects can hit you hard, even if they are small objects. They have bits and pieces of the neuronal networks which interest Thom. His job is to discover those bits and pieces.9

It is also quite likely that the students are missing networks that tie things together. It could even be something as simple as vocabulary. They may not quite have a good network for the word momentum, for example. They may have the parts that need to be connected, but that key last connection hasn’t ever been formed. And if we don’t know what connections are missing, we won’t know how to teach them.

Tangles

Each learner brings his own special set of neuronal networks to class. There’s nothing we can do about that. They really can’t check them at the door!

These networks are a true tangle, some with branches hanging off one side or the other, some drooping bedraggled on the ground, some sticking bare and brave into the sky, some with weak connections to others, some with strong connections to others. We see this in our experience with students as we come to know about their needs, their misunderstandings, their partial ideas, and their talents and skills.10

Our inclination is to straighten out this tangle. We want to correct what we find to be in error, trim up the loose ends, prune out the useless branches, and construct new ones that will be of more value. It’s simple! We will just explain what is right and what is wrong, and that will be that!
We cling tightly to this illusion. An example remains vivid in my mind. One of our teachers was complaining bitterly about a certain misunderstanding her students always make, when a second teacher suggested, in total sincerity, “Well, that’s simple. I would just list the five reasons why that idea is wrong on the board, and take care of it immediately!”

But we know that this doesn’t work. It’s not possible to get in and fix things.

This is one of the most important, and yet simple, ideas that biology can give teachers. We must let our students use the neuronal networks they already have. We cannot create new ones out of thin air or by putting them on a blackboard. And we cannot excise old ones. The only recourse we have is to begin with what the learner brings.

Tangles in the Classroom

I learned of another example of the tangle we make of learning through the research of a friend of mine, Kathy Schuh. Her work explores knowledge construction by children, focusing particularly on the idiosyncratic connections they make in classrooms based on their prior experiences. Kathy observed classroom lessons and took notes on the environment and classroom interactions, particularly those comments and questions that seemed to be unique to each child. Then, after class, she asked individual children about the content of the lesson and other things that went through their mind during the lesson.

From this information, Kathy constructed a type of map to show the connections that the child made. One of these maps is shown below. The lesson was about Charlemagne, so you should find your starting point by finding where he shows up on the map. This is just the result for one student in one class, but Kathy studied many students, and the individual maps of different students are all complex and unique.11

Of course, we know that this tangle happens in all classes, all the time. Even the most focused of brains finds itself bouncing from neuronal network to neuronal network in a lecture or during a lesson. And the connections are totally unpredictable. A single word can send a mind off through a tangle of neuronal network underbrush.
In Thom’s office

When I visited Thom in his office the next day, I found him making paper airplanes and gliding them toward the corner wastebasket. He smiled. “You think I planned this, don’t you? Or maybe you think I spend most of my time throwing papers around!”

I grinned and sat down.

“I have been thinking,” Thom went on. “Maybe I have a better chance of connecting with the neuronal networks of my students if I use more concrete examples that they already know, like paper airplanes.”

He pulled out three airplanes from the wastebasket. One was long and sleek with a very sharp pointed nose. Another was folded with a blunt nose and had wider wings. The third was the worst. Not
only was the nose flat, and the wings broad, but the back half of both wings was folded up vertically. That plane was not going to fly far at all!

Suddenly it struck me. “Very clever Thom,” I exclaimed. “I bet your sleek plane will fly the longest, because it gives the least resistance. Your students will get that in an instant. Now, if you could only make one with no resistance, how long would it fly?”

“Conservation of momentum!” Thom said.

“You could talk about it for a long time, and use lots of equations and graphs, but I bet they will get the basic idea almost immediately with this example,” I said.

“Worth a try.”

But then he grew more serious. “Still, I’m worried. What will they think! I might lose control and pretty soon everyone will be throwing things around the room.”

“Yes,” I said. “It will be a challenge to think of ways you can keep them on task.”

“That’s why I have you,” he replied slyly. “But another thing. I’ve also decided to pay a lot more attention to what they already know. I never did this in a physics class before, but I am going to ask them to write out what things mean to them in English words and sentences. It seems to me that I have been assuming that their neuronal networks are just like mine. But, whatever, I intend to find out!”

“Like what?” I asked.

“Well, for one thing, what does momentum mean to them, in their own words? Using their own neuronal networks? Or resistance? Or mass?” He almost seemed excited.

I know I was excited, but I also felt a little wary. “It looks like you have some good plans, but don’t expect every student to like them,” I said slowly. “They also have neuronal networks about how teaching should be done and about what happens in physics classes. What they already believe could get in the way. . . . Not for all of them, of course,” I added quickly.

He never missed a beat. “I know that,” he said. “But it’s worth it in my judgment. I’ve got some new connections in my own neuronal networks, and they will be hard to change, too! These ideas have momentum. They can overcome a lot of resistance. Even if they won’t fly on forever!” And he laughed as heartily as I ever heard him.
Finding Out about the Neuronal Networks of a Learner

Roger Schank says, “A good teacher is not one who explains things correctly, but rather one who puts things in an interesting way.”\textsuperscript{12} What this suggests is that such a teacher knows what will be interesting to his students. He knows about existing neuronal networks.

We have talked about starting with the concrete experiences that we believe our students understand. And Thom has the idea that he can find out about existing neuronal networks by asking his students to write out their ideas about physics in words rather than equations. These are both good suggestions, and there may be others we can add to the list.

One method I have used in my small classes is to have students explain their previous experience and ideas about the subject material. Specific questions can be used to get this going. For example, I might ask the students to write out their idea of a gene or draw a picture that conveys their idea. Usually, they are not allowed to use technical terms. Then I ask them to exchange their responses, and each student then tries to explain what they think their classmates are trying to say. Inevitably, as they hear their ideas described by another person, an active discussion will ensue, which uncovers a lot about the neuronal networks of each student. I ultimately try to use the information I get in these sessions to guess what each student will find interesting.

You undoubtedly will think of other ways to learn about the neuronal networks of your students, if you become convinced that it is as important as I say it is. Most teachers are wonderfully creative, once they come around to a new idea—once something fits in with their own neuronal networks!

What We Have Learned about What We Already Know

In these conversations with Thom I’ve tried to point out some of the key ideas in this chapter. Here are ten ideas that seem worth remembering:

1. All students have prior knowledge that affects how they respond to our teaching.
2. The prior knowledge of students is not an ether; it is physical, real, and persistent.
3. If we ignore or avoid prior knowledge, it will hinder our teaching.
4. Prior knowledge is complex and personal.
5. Students are not necessarily aware of all their prior knowledge.
6. Writing assignments are helpful in discovering prior knowledge of students.
7. Prior knowledge is likely to be concrete; teachers should begin with the concrete.
8. Concepts and broad principles should be developed from specific examples.
9. Teachers should expect and respect the tangles; it is not our job to set them in order.
10. Prior knowledge is a gift to the teacher; it tells us where and how to start.

Next Steps

I have said repeatedly that teachers should build on existing neuronal networks. They are a tool to be used. And I have also said that those networks cannot be eliminated. They are persistent and powerful.

But learners do improve and grow in their knowledge. If prior knowledge turns out to be useless, they stop using it and learn new ideas. How do these things happen if prior knowledge is so persistent? What produces change in neuronal networks?

These questions are the topic of our next chapter. As we address them, we will see more clearly how the teacher fits in and why I claim that teachers physically change brains.

Notes

1. I use the term neuronal networks rather than neural networks because of the rather specific meaning that the latter term has gained in cognitive science. Neural network has come to mean a network of connections in computers rather than those in the head.
2. The subject of so-called “naive physics” has been examined quite extensively. Long lists of the incomplete or inaccurate ideas that students may hold about the physical world can be found in the literature, but educators seem uncertain about what to do about this. To get a sense of this uncertainty, examine M. Reiner and colleagues, or K. J. Pine and D. J. Messer in Cognition and Instruction 18 (2000), pp. 1–51.

4. The number of neurons in a brain is often described dramatically. However, it should be pointed out that this number is not different than the number of cells in any other tissue. There are approximately 100 million cells in a gram of any tissue.

5. The number of connections per neuron may be as high as 100,000 for some types of highly branched neurons.

6. Occasionally it is noted that the potential number of connections in the brain is higher than the number of atoms in the universe. This “potential” number arises if we assume that every neuron is connected to every other neuron. But this is just a game. As much fun as it is, the brain could not work if this were true, and the added mass from all those dendrites and axons would produce a head at least 1,000 times heavier than it is.

7. As with all the other stories in this book, the first episode with Thom, described at the beginning of this chapter, is based on actual experiences of the author. However, this episode and the final one at the end of the chapter are fictitious. They are conversations I wish I had had.

8. I am not saying that all abstract ideas are demonstrable in the concrete world or through our experience. Some concepts of physics appear to be devoid of any satisfying physical representation, such as the dual nature of the electron or curved space. But from my conversations with physicists, I also suspect that these ideas leave a trace of discomfort even in the brain of the expert. We may be forced to accept them because of a mathematical result, but I’m not sure we ever get really comfortable with them.

9. This is apparently what the Socratic Greeks believed. Education, in their view, consisted of helping the learner discover what was already in the brain.

10. Of course these generalizations apply to all of us, not just students. We look for understanding and order in student thinking because we have created order in our own minds about the subject. But that order is not preordained. Sensory experience brings things to us in a random fashion, and our meaning-making brain connects them up in no particular order. That’s one of the reasons our brains work so well. We can take in whatever random nature delivers to us, remember good amounts of it, and eventually make meaning of it, creating our own personal order.
