Whether you’re a parent interacting with one adolescent or a teacher interacting with many, you know teens can be hard to parent and even harder to teach. The eye-rolling, the moodiness, the wandering attention, the drama. It’s not you, it’s them. More specifically, it’s their brains.

In accessible language and with periodic references to Star Trek, motorcycle daredevils, and near-classic movies of the ’80s, developmental molecular biologist John Medina, author of the New York Times best-seller Brain Rules, explores the neurological and evolutionary factors that drive teenage behavior and affect both achievement and engagement. Then he proposes a research-supported counterattack: a bold redesign of educational practices and learning environments to deliberately develop teens’ cognitive capacity to manage their emotions, plan, prioritize, and focus.

Attack of the Teenage Brain! is an enlightening and entertaining read that will change the way you think about teen behavior and prompt you to consider how else parents, educators, and policymakers might collaborate to help our challenging, sometimes infuriating, often weird, and genuinely wonderful kids become more successful learners, in school and beyond.
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Introduction

Whether you’re a parent interacting with one adolescent or a teacher interacting with many, you know the truth: teens can be hard to parent—and even harder to teach. When I drop the phrase “attack of the teenage brain,” you nod knowingly. Perhaps the word “attack” even strikes you as an understatement.

I have a message for any adults currently sheltering in place as the Battle of Adolescence rages around you: you’ve come to the right book. We’re going to talk about how to parent and teach teenagers, focusing primarily on education-related issues. We’re also going to envision what a high school might look like if teen brain development were its optimal goal, and if we enlisted the cooperative efforts of parents and educators to help our challenging, sometimes infuriating, often weird, and genuinely wonderful kids get what they need as they fight their way toward adulthood.

Maybe you’re too young to remember *Attack of the Teenage* anything. So let’s kick things off with something still long-in-the-tooth, but a bit more contemporary: a scene from *Star Trek III: The Search for Spock*.

It opens with stable, logical, good-old Mr. Spock acting anything but stable, logical, or good-old. In the scene, he’s
a teenager, and we see him yelping at the moon and crying inconsolably—the Vulcan equivalent of stomping upstairs and slamming the bedroom door. We’re told he is experiencing pon farr, a mysterious hormone surge that happens to beings of his race every seven years and must be sexually requited. Sounds to humans like a nightmarishly reoccurring puberty.

Mr. Spock is hardly alone in being bewildered by the seeming illogicality of sexual maturation, even if his struggles are constrained to a fictional once-every-seven-years itch. Whether in the 23rd century or the 21st, adolescence seems as inexplicable to the long-suffering human teens experiencing it as it does to long-suffering human adults witnessing it. To the research world, however, adolescence is neither inexplicable, illogical, nor unfamiliar. Puberty is as old as the Pleistocene and as recent as next week. I hope, in these pages, to use the sturdy tools of brain science to show just how much more familiar we are becoming with it, describing in detail the warp and woof of teenage brain development.

I am inviting you along on this journey not simply because the brain is an amazing place for teachers and parents to boldly go exploring, though it certainly is. This book has an explicit ulterior motive: I hope to show every teacher and parent on the planet why they should know and care about a specific cognitive gadget called executive function, and I hope to make the case for altering the educational landscape to help teens use their executive function skills more efficiently. This is, I believe, the missing link when it comes to improving secondary education.

I’ll argue that more than any other single intervention, boosting executive function is a dependable method for improving teen academic achievement. And it also moonlights as the best way for frustrated parents to guide their pon farr–soaked charges. There is a constellation of peer-reviewed papers, mostly from the neurosciences, shedding light on the academic and social benefits of supporting executive function development.
The sunny light they radiate can warm adults who spend their days teaching teens on even the most behaviorally frigid days.

**Getting to the Heart of the Brain**

My first task in this book is to describe what executive function is; my second is to guide you through the mystery of why teens behave as they do; my third is to examine proven ways to enhance executive function and consider the consequences those findings have for education. Written primarily with teachers in mind, with an eye toward parents who can benefit as well, this book includes a fair amount of peer-reviewed behavioral psychology and neurobiology, which may sound scary or, worse, too esoteric to be truly useful.

Perhaps I can offer some reassurance. I am a developmental molecular biologist with research interests in the genetics of psychiatric disorders. I have spent most of my career as a private research consultant, working with companies ranging from biotech firms interested in the genes of schizophrenia to computer companies interested in anxiety. My participation in these advisory activities has led to many hours interacting with smart, highly motivated professionals whose last biology class occurred when they themselves underwent *pon farr*. So I promise to keep the jargon to a minimum, the concepts as clear as possible, and the prose liberally sprinkled with anecdotes and metaphors. I will insert the neurobiology where necessary, but always in pursuit of the goal of explaining executive function as clearly as I can.

**Two Bits of Background**

In support of this vow of clarity, I have two pieces of background information to share before we embark. The first concerns how scientists view the origins of human behavior.
We used to regularly engage in silly intellectual food fights about whether behaviors were caused by nature or by nurture, whether they were hardwired in human genes or softwired in the culture. We stopped fighting about this when our research told us we were using the wrong conjunction: it’s not nature or nurture; it’s nature and nurture.

To use a familiar example, you might be genetically programmed to achieve a certain height. Genes are proxy for nature here, under the regulatory control of human growth hormone. If you aren’t fed properly during childhood, however, your growth may be permanently stunted. That’s nurture, overriding any executive order your height hormone may try to issue. Both nature and nurture serve as chefs in this kitchen, and together, they dish out how tall you become. This duality is also very true of executive function, as I will explain later.

The second piece of background has to do with some frankly off-putting attitudes a few adults (not you, of course) have about teens. Some think adolescents are simply defective grown-ups, that there is something “wrong” with them when they act like horny aliens from Mars—or Vulcan. There is no question that adolescents aren’t adults, but I hope to show that “defective” is hardly the right word to describe them. We’ll discover that teen brains were genetically wired to perform specific functions, mostly related to solving problems of genetic diversity eons ago. If adolescents seem imperfect now, it’s only because most of the obstacles their brains were wired to traverse no longer exist, and we haven’t sojourned long enough in organized society for adolescent brains to get the memo. As the father of two teenagers, I can testify that teens make errors all the time. But there’s a big difference between an error and a flaw.

If you can hang with me through all this, I promise to keep the neuroscience approachable and ensure that the intellectual load-bearing is done by peer-reviewed research. I promise to clearly explain how it relates to your angry face in the mirror.
and to the teenagers in both the *Star Trek* universe and in ours. And I'll draw it all together to show how we should tailor educational experiences to further teenagers' academic progress and social development.

Deal? If so, then I invite you to read on. We've got a whole galaxy of fascinating things to explore.
Part I: A Bridge Over an Educational Chasm

This part consists of a single problem-solving chapter. The pain-point is one of the shames of American secondary education—our high schoolers’ embarrassing international test scores. The remedy involves the cognitive gadget called executive function, which is both defined and explained.

It’s a “let’s-roll-up-our sleeves” background for the rest of the book, which involves reimagining what a secondary educational experience might look like if optimizing teen brain development were its primary goal. And it all starts with a motorcycle, ridden by a man who didn’t even finished high school. . . .
All About Executive Function

You really question Darwin’s assertion that only the fittest survive when you consider the antics of famed motorcycle daredevil Evel Knievel.

Back in 1974, Mr. Knievel got it into his head to jump the Snake River Canyon and have the attempt broadcast live on television. He announced that the stunt would occur near Twin Falls, Idaho, and that he’d jump from the canyon’s south cliff to the north one, spanning a suicidal distance of nearly three-quarters of a mile. Because no Harley made has that kind of engine power, Knievel employed what was, for all intents and purposes, a two-wheeled rocket ship dubbed “The Skycycle.” The spectacle ended up as one of the most famous nonevents in the checkered history of television, because the major networks refused to cover it.¹

The good news was that Knievel survived. The bad news was that the jump was a bust. It began well enough, with the rocket roaring to life under the secure watch of the guy who built it, a former Naval rocket engineer. The Skycycle’s parachute system wasn’t as well behaved, unfortunately. It deployed early, almost as soon as the daredevil was airborne. Knievel drifted slowly,
safely, to the canyon bottom, the wind blowing him back to the south side to a spot just below his point of origin. The Snake River Canyon would remain un-jumped for decades to come. When stuntman Eddie Braun accomplished the feat in 2016, he used a rocket-powered motorcycle designed by the son of the engineer who had developed Knievel’s.

I’m going to use this jump by Knievel, a true American original, to describe something puzzling about another American original, the K–16 education system of the United States. To understand where the parallels lie, let’s begin—perhaps unconventionally—at the end.

All Steak, No Sizzle

Much empirical evidence exists to support the self-serving, chest-puffing observation that higher education in the United States is the envy of the world. According to the research magazine Nature, nearly two-thirds of the world’s highest-rated universities are American, including three of the top five. The ratings may be deserved, if award-winning productivity is any measurement. More Nobel prizes have been given to U.S. scientists than to scientists in the next five represented countries combined. The United States is especially strong in natural sciences Nobels; most are awarded to people who are (or were) employed by those top-ranked universities. Think of higher education in the United States as the terminating north cliff goal of Knievel’s Snake River Canyon attempt, only with a happy ending.

In this metaphor, U.S. elementary schools are Knievel’s starting point on the south side of the canyon, and they are similarly solid. The federal government (in the form of the National Assessment in Educational Progress, or NAEP) has been measuring school performance for decades, and its findings show that elementary schools are doing a pretty good job. Although U.S. students are well-known to be underperformers in math, NAEP’s
findings show that our 4th graders’ elementary math scores have increased 11 percent since the early 1970s. Reading scores have also improved—up 6 percent—in the same kids and over the same time span. American elementary schools’ scores have been rising like yeast for years, and they are sufficiently robust, comparing favorably with schools in other countries.

So the two sides of the U.S. education “canyon” are in good shape. And if all you had to go on were these two data points, you’d think the system could be drawn as a statistically pleasing straight line that begins in quality elementary education and terminates at the pearly gates of Nobel Prize–festooned colleges.

Unfortunately, we’re going to have to fasten our seat belts for the bumpy landing. A comparison of the scores of recent U.S. 17-year-olds to ones put up by 17-year-olds 40 years ago shows not one whit of improvement in math or reading. Teens today actually scored worse in science. This means kids who were tested back when Pong was all the rage in video games achieved at basically the same levels as kids who grew up with Grand Theft Auto. The score differential for minority and disadvantaged youth shows even less progress.

This stasis is embarrassing, especially when U.S. language arts and math scores are compared with those of the rest of the world. Our 15-year-olds come in at a depressing #24 on the 2015 Programme for International Student Assessment (PISA). And for math, we are #36 out of 40. Says noted psychologist Laurence Steinberg:

Over the past forty years . . . and despite billions of dollars invested in school reform, there has been no improvement—none—in the academic proficiency of American high-school students. It’s not just No Child Left Behind or Race to the Top that has failed our adolescents—it’s everything we have tried.

The italic emphasis is Steinberg’s, but his pessimistic outlook is ours for the keeping.
And the bad news keeps rolling in, especially when our students try scampering up the far side of our educational chasm, banging on the doors of our lofty universities’ admissions offices. To put it bluntly, many high school graduates just aren’t ready for college. About 20 percent of starting freshmen spend time in the remedial education penalty box, and for an embarrassing reason: they didn’t master the basics necessary to compete in world-class institutions.

It’s even worse for students entering community colleges. About 50 percent need additional preparatory work, except in California, where the figure is 80 percent. And here’s the weird thing: those Californian students in need of remediation graduated from their secondary schools with a B average, in the upper third of their classmates. To make matters worse, many students who enroll in these “developmental courses” get stuck in them like a dinosaur in a tar pit. After six years, only 16 percent of the enrollees went on to get a degree.

**A Bridge Named Executive Function**

These achievement data are ugly for sure, but they’re not the whole story of U.S. education. There has been some recent improvement in grades and even graduation rates, especially for underserved populations. Still, that isn’t much reassurance, especially when budgetary issues are taken into consideration. Higher graduation rates don’t translate to much if you have to spend $3 billion a year—as we do—just to get kids up to scratch. That kind of money should help make every kid an Eddie Braun, but we still have far too many Evel Knievels.

Obviously, we need to build a superior rocket-cycle—or even better, dispense with the quick fix altogether and build a bridge. That’s what this book is all about: how to span the yawning academic chasm between strong elementary education and strong college education. We are going to use a modern neuroscientific
understanding of teen brain development as the wood, hammer, and nail of the construction. This bridge even has a name, though it may sound more like something from a business school than a brain science concept: executive function.

**Of T. Rex and Marshmallows**

Executive function (EF), defined in its baldest operational terms, is the ability to get something done—and not punch someone in the nose while doing it. That’s a useful bit of oversimplification; to go more in depth, I’d like to start by explaining part of EF’s origin story. To do that, I’ll discuss the discovery of a dinosaur named Sue, then quickly move to marshmallows.

Obviously, I have some explaining to do.

Sue wasn’t supposed to be discovered. The research team that found her had spent a summer in South Dakota digging for cretaceous-era vegetarians and were packed up and ready to head home. Then a flat tire delayed the group’s departure. While the tire was being fixed, self-taught paleontologist Sue Hendrickson wandered off for one last look around the geological neighborhood. It was an impulse that made her career. Spying a few curious-looking rocks at the foot of a nearby ridge, she looked up and noticed an even more curious protrusion jutting off the cliff’s face.

The trip home could wait. Investigation of the protrusion revealed it to be a bone of the most intact fossilized *Tyrannosaurus rex* ever found. Almost 90 percent of skeleton was there (a paleontological find is considered monumental if just 50 percent of the bones are discovered). The famous fossil was named Sue, after her discoverer.13

This tip-of-the-iceberg phenomenon—that what looks at first to be a small finding can turn out to be a really big discovery—isn’t limited to paleontology. You can see the same principle working in one of the most well-known experiments in the field of
behavioral science, the one that eventually exposed the phenomenon of executive function. There, marshmallows took the place of digging equipment and fancy research-grade plasters.

Walter Mischel’s legendary experiments at Stanford University in the late 1960s dealt with how children resisted temptation. In the experiment’s most famous version, following a premise right out of TV’s *Let’s Make a Deal*, Mischel offered a series of 4-year-olds the choice of eating one tasty marshmallow immediately or waiting for 15 minutes—alone in the room, just the child and the uneaten marshmallow—after which he or she would receive two tasty marshmallows to eat.\(^{14}\)

What happened could be difficult to watch. Most kids took the deal, though very few were able to follow through. Some kids ate the marshmallow within 30 seconds of the researcher leaving the room. Some valiantly resisted for a while, sitting on their hands, turning their backs to the marshmallow, or counting to 10 before caving in. A handful of supremely self-controlled subjects held out for the entire 15 minutes.

Records of each participant’s results were stored for a long time while these kids percolated through the U.S. education system and into adulthood. Years later, Walter Mischel and his colleagues looked up hundreds of the young marshmallow experiment veterans to see how they had turned out.

What they found was both depressing and encouraging—and ultimately, groundbreaking. The kids who exhibited little self-control as 4-year-olds still exhibited little self-control years later. They achieved poorer grades and were less popular in school. They were more likely to be obese and more prone to drug abuse. The kids who held out for the whole 15 minutes also displayed extraordinary self-control years later. They got better grades in school and were more socially competent. They were physically fit and didn’t abuse drugs. The data were fine-grained enough to conclude that the 15-minute holdouts scored, on
average, 210 points higher on the SAT than the kids who caved within half a minute. The marshmallow experiment proved to be the Sue-bone protruding from the cliff. Further investigations into self-control revealed an entire body of behavioral tendencies that, as a group, were ultimately termed “executive function.” This area of investigation is still very active, and for a very important reason: executive function correctly predicts aspects of a student’s future. The accuracy of such statistical palm reading is about as rare in the behavioral sciences as prehistoric soft tissue is in paleontological finds. And one of the hottest areas of research involves the teen brain, with its hallmark developmental feature being the elaboration of executive function.

I will restate what I wrote in the Introduction—every teacher of teenagers should understand what executive function is and how it develops in adolescent brains—and underscore the urgency of such a claim by detailing how executive function comes by its predictive, prophetic power.

**One Plus One Plus One Equals More**

Despite the simplicity of its two-word label, executive function is tricky to define. It doesn’t help that many scientists disagree on exactly what the darned thing is, managing to agree on just a few basic tenets. Fortunately, we can combine and recombine these few basic tenets to assemble a host of explanations for our external actions.

I am reminded of the purchasing habits my wife and I developed when we were in graduate school, and usually as broke as public television. In those poorer times, we were always on the lookout for a good deal on anything, down to the clothes we bought. My wife taught me the money-saving power of creating a mix-and-match wardrobe by buying a few elemental articles
of clothing combining them in different ways for different occasions. Similarly, EF encompasses a bewilderingly complex collection of human behaviors, but at its core are three simple, easily combined, and easily understood behavioral elements.

A Complex List

Let’s look at an example of executive function in action.

Imagine your supervisor is yelling at you. You are startled, because he rarely yells at anyone. The ranting continues, and soon you want to punch him in the nose. But you don’t. You engage in some emotional editing because you understand what the consequences of your desired action would be (loss of job security, impending assault charges) and you take responsibility for avoiding those consequences. You can perform this emotional editing because you’re able to respond to situations as they occur, weighing advantages, managing risk, and imagining in advance what might happen if you choose violence. Your ability to respond in this fluid manner allows you to move from your present anger and into the future, if only for a few seconds, without losing track of your current circumstances.

As you begin to calm down, you contemplate your boss’s outburst. You wonder what could have triggered his unusual behavior by trying to empathize, shifting your perspective to his. If you are successful, rationality returns, imposing order in your emotional life despite disparate inputs. Oddly enough, you can hold all these inputs and reactions in your brain’s short-term memory banks long enough to complete the appeal to the better angels of your nature, and the situation comes to a nonviolent resolution.

According to most researchers, the complex wardrobe of behaviors that make up executive function boils down to mixing and matching a trio of foundational behaviors: (1) response inhibition, (2) cognitive flexibility, and (3) working memory. Let’s move from the analogy to the specifics of these concepts.
What Researchers Think

Here’s one widely accepted definition of executive function:

The executive functions are a set of processes that all have to do with managing oneself and one’s resources in order to achieve a goal. It is an umbrella term for the neurologically-based skills involving mental control and self-regulation.17

Executive function’s defining element is in the first sentence: in order to achieve a goal. From a Darwinian perspective, the overall goal is survival. But since the brain decided to hang its evolutionary fate on fickle social interactions—a topic we’ll take up in a minute—it had to incorporate enough flexible gadgets to keep us from killing ourselves. The definition thus consists of two hopelessly mixed metaphors: a combinatorial behavioral wardrobe that allows you space to temper your urge to punch someone in the nose with an awareness of the consequences of your actions.

The Neuroscience of Frank Capra

The movie It’s a Wonderful Life (1946) was filmed decades before anyone had researched executive function. Yet one scene in this classic movie depicts, in grayscale glory, one of the clearest examples of adolescent EF I’ve ever seen.

Young George Bailey, while helping out the town pharmacist, Mr. Gower, was supposed to deliver a medicine to a sick boy. George realizes Gower gave him the wrong medicine—a poison, in fact. He returns to the pharmacy, bad stuff undelivered, and happens upon an opened telegram conveying tragic news: Gower’s son has just died.

The pharmacist is burning with the acid agony of fresh grief. And he’s drunk. Blurrily furious that the meds were not delivered, Gower lunges at George, boxing his ears, drawing blood, staggering through sobs and tremors. “Don’t you know that boy’s sick?” he croaks.
Little George Bailey’s response is amazing. He’s under violent assault, but he doesn’t strike back. Instead he cries, “Mr. Gower, you don’t know what you’re doing. You put something wrong in those capsules. I know why you hit me. You got the telegram and you’re upset. You put something bad in those capsules. It wasn’t your fault, Mr. Gower!”

Gower discovers George is telling the truth, falls to his knees, and embraces him in alcohol-soaked gratitude. There will be no further violence that morning, only understanding—all due to George’s clear-eyed choice to comfort an old man enduring the worst day of his life.

Powerful stuff, this executive function.

**The Executive Function Trinity**

As stated before, most scientists concur that EF includes a trio of interactive elements (see Figure 1.1).

*Response inhibition* (also called effortful control, self-control, emotional self-regulation, and impulse control) involves ignoring a compelling natural tendency in favor of another behavioral option. Resisting sensory temptations (e.g., adultery, ice cream sundaes, designer shoes) or not striking back at someone who is threatening (Mr. Gower) are examples. The core behavior involves controlling what we pay attention to, ignoring certain stimuli, and attending to others.

The second element, *cognitive flexibility*, allows individuals to adapt to changing circumstances with the liveness of a Cirque du Soleil acrobat. It includes the ability to see objective problems (or subjective people) from multiple perspectives, switch perspectives, and notice when perspectives switch. George didn’t strike back at Mr. Gower because, having seen the telegram, he was able to assess the situation from the viewpoint of the grieving pharmacist. Mr. Gower exhibited perspective-switching too,
changing his behavior when he realized George had not endangered the sick boy’s life, but saved it.

The third component is working memory, a retrieval system that is sometimes called short-term memory. Researcher Alan Baddeley (who looks unnervingly like Henry Travers, the actor who played angel Clarence Odbody in It’s a Wonderful Life) showed that working memory is where information is stored temporarily in the pursuit of a goal. It is made up of a series of buffers, each assigned to store different things. One buffer, termed
the phonological loop, holds verbal information. Another, called the visuospatial sketch pad, transiently holds images and other spatial inputs. There’s even a buffer designed to keep track of the others named the central executive. A number of years ago, Baddeley added a final category, the episodic buffer, which holds information couched in the form of stories.

Of Darwin and Genetics

Neural substrates underwrite these three behaviors with the thoroughness of a stress-tested bank. Like all biological tissues, these nerves were forged in the iron furnaces of evolution. Researchers are beginning to understand the selective pressures—the Darwinian hammers and anvils—that shaped the nerves during humanity’s collective Serengeti sojourn. They took form not because humans were so strong, but because we were so weak.

I know that sounds oxymoronic. In our fragile, naked, not-very-hairy physical bodies lies little hint of any internal power that could crown us Earth’s apex predator. Yet that’s what humans became. If we relied purely on corporeal evolution, we might have had to wait 24 million generations to become big and strong and essentially invulnerable, like elephants (who actually did have to wait 24 million generations). The anthropological record shows we didn’t wait those gazillion years to become Earth’s most dangerous badasses, and yet here we are, indisputably in charge. What in the world happened?

Enter executive function, taking center stage like a diva.

It’s a strange kind of prima donna. Rather than causing us to be consistently narcissistic, executive function allows us to be steadily cooperative. With brains capable of not only understanding one another’s psychological interiors but also tolerating one another’s psychological interiors, we learned to coordinate our behaviors. From there, humans began
cooperating to pursue common goals, like systematizing our hunts and dividing our labors.

We needed not big strong bodies to do this, but big strong brains—and developing those allowed humans to spend a lot less time in the evolutionary gym. Executive function guided this process. It lubricated our social interactions so that coordination often defeated confrontation. Then it defeated every other species. Those ancestors who excelled in EF lived long enough to further excel by passing on their genes.

This statement suggests that proficiency in EF is as heritable as a family fortune. Here’s the shocker: it is. The title of the research paper by the team that discovered this fact says it all: “Individual Differences in Executive Functions Are Almost Entirely Genetic in Origin.” According to these researchers, executive function has the highest heritability for a complex behavioral suite ever recorded, with the individual variance weighing in at a whopping 99 percent.21

Yep, the ability George Bailey has to understand Mr. Gower lies somewhere in George’s genes. And in ours, too. Genetics aren’t the whole story, of course. There’s that nature/nurture stuff to contend with (data exist demonstrating that it’s not only willpower that influences what we do with marshmallows at age 4, for example; the perceived reliability of the reward is a factor, too).22 But without invoking the double helix of DNA at some point, the Darwinian picture is woefully incomplete.

**Hunting Like a Little Girl**

The image on the cover of *National Geographic Traveler* magazine captures a smiling 13-year-old girl straddling a wind-carved Mongolian mountaintop; on her arm is a flapping eagle that is literally as big as she is. Her name is Aisholpan Nurgaiv, and she is the youngest Eagle Hunter—make that Eagle *Huntress*—in the world.23
There are two remarkable things about Aisholpan. First, she is blessed with a spine made of titanium. Girls in Mongolian culture aren’t supposed to hunt with eagles; it’s a fully ritualized falconry-meets-grocery-shopping activity with a big cultural sign on its neck that reads “males only.” Yet her determination to learn was as unmoving as the Altai mountains of her homeland. Facing gale-force winds of social rejection, Aisholpan trained relentlessly in the unforgiving winters of Western Mongolia (the grown men of the film crew who were following her around could barely keep up). Even when she became successful, the male elders in her community made excuses to explain away her accomplishments, saying she had a great bird or a great coach, or she was just seeking publicity.

The second remarkable thing about Aisholpan is the talented organ topping that metal spine. She is whip-smart and ambitious. She’s learned Turkish and English. She snagged a scholarship to a school in Mongolia and wants to be a surgeon. The film eventually made about her, The Eagle Huntress (2016), became wildly successful, and some of its proceeds will be used to develop Aisholpan’s brain further by funding her pursuit of higher education.

It’s no coincidence that extraordinary self-control and extraordinary intellectual accomplishment are joined at the hip. Put simply, this combo gives kids the intellectual talons necessary to tear into hard problems. The twin peaks of response inhibition and academic achievement predict success in virtually every country where such behaviors have been studied. That Aisholpan Nurgaiv is an exemplar of a fascinating area of brain science is probably not something the camera crews would have ever expected. And yet she is.

Self-Control

Aisholpan’s determined self-control is as obvious as the steely grin on the Eagle Huntress’s face. There are several definitions
for self-control, and the responsibility and determination that fortifies Aisholpan’s character easily fit most of them. Scientists Roy Baumeister and his colleagues have even invented psychometric tests to measure the behavior. These tests, now very much the gold standard used to measure this aspect of executive function, have been found to be both reliable and valid.24

Not only that, these tests are prophetic. Put simply, executive function acts as a scientific Nostradamus. It can actually predict how kids will turn out as students, and then go on to predict how they will turn out as adults. Whether you examine cross-sectional data, longitudinal data, associative studies, or direct interventions, high scores on executive function measures predict future success at teenagers and adults. And it’s practically the only thing that does.

Here’s how Baumeister and Tierney put it:

When researchers compared students’ grades with nearly three dozen personality traits, self-control turned out to be the only trait that predicted a college student’s grade-point average better than chance. Self-control also proved to be a better predictor of college grades than the student’s IQ or SAT score.25 (emphasis in original)

The fact that executive function separates rock star from rock bottom is the primary reason teachers (and parents too) should know about EF and focus on it when interacting with the adolescents in their charge.

**Weed-Whacking**

I realize that linking executive function and academic (and future) success so strongly is provocative. There are researchers who are skeptical of the connection. I recall one review article that went so far as to bluntly dismiss the assertion that EF boosts student outcomes in reading and math, stating: “No compelling evidence that a causal association between the two
exists." Yet another paper claims just the opposite and does so decisively, as you can discern from its title: “Executive Function Predicts Reading, Mathematics and Theory of Mind During the Elementary Years.”

What can we do with this conflict? I’ll have more to say about the tenuous relationship between correlation and causation in a little bit. Suffice it to say, the preponderance of data appear to cluster around executive function like adoring fans at a book signing.

Here’s the bottom line: as a teacher, you want your classroom populated with as many Aisholpans as you can find. They get along better with teachers and are popular with peers. They achieve better academic outcomes in part because they have better study habits. They have terrific attendance records. They start their homework earlier, spend more quality time with it, and are less seduced by electronic screens, the great Western digital temptress.

The data are becoming granular enough that we can predict which cognitive gadgets relate to which specific classroom skill. Flexibility scores all by themselves predict success in mathematics. We also know that when all three pistons of executive function—response inhibition, cognitive flexibility, and working memory—are firing at the same time, reading comprehension goes up. No wonder kids with strong EF scores do better after they traverse the crevasses of puberty and find their way to college.

Of course, these warm-and-fuzzy data describe kids with high executive function, which is only one side of the story. What about those with low EF? Do their scores also predict their future—one that’s perhaps not as warm and fuzzy?

The answer is depressing, with the most striking results coming from the behavioral work. Kids with low self-control scores are more likely to be expelled from preschool (it starts that early). They often percolate through their elementary years with anger management issues (tantrums) and become more
socially aggressive with age. To no one’s surprise, their grades in primary school stink. By adolescence, these kids are at greater risk for every behavior we’d rather they say no to. They’re more likely to engage in unprotected sex, abuse drugs, and enter the juvenile system. And their grades still stink.

Other Cultures

Amid these darkening data, I would like to light a candle.

First, let me say that I believe deeply in the incandescent power of world cultures interacting with one other, which is something I see in my profession and across the country every day. The research groups around our universities generally look more like the United Nations than they do many parts of the United States. There’s a lot of hope in this diversity, especially in the passive transfer of behavior (including executive function; more about this transference later).

Nonetheless, I admit becoming as hot as a Szechuan peppercorn when I picked up the 2011 best-seller Battle Hymn of the Tiger Mother by Amy Chua, where I read about behaviors that seemed more a blowtorch than a hope-inspiring candle cultural amalgamation. Chua allowed her two daughters no playdates. No boyfriends, either. They studied six hours a day and were drilled with music lessons using a method so draconian it was detailed in the Wikipedia entry for the book. One adolescent daughter was told that if a complex piano piece wasn’t mastered in 24 hours, her mother would dismember her dollhouse, then donate the pieces, one at a time, to the Salvation Army. Tiger Mom didn’t let her take a break—not for dinner, not for the toilet, not for a drink of water—until she nailed the piece. Which eventually she did.

After finishing the book, I was left with several candle-lighting impressions. First, it was clear to me that Chua hadn’t written a parenting book; she’d written a memoir, and much of it, as she
says, is distilled self-parody. Second, Chua’s children became wildly successful, graduating from the most prestigious universities in the world. “We are a close family,” the piano-playing daughter said in an interview. “Even when there was a lot of screaming, that was work. When it was over, that was family time and we’d go upstairs and watch movies together.”

Third, there was something vaguely appealing to me about the Tiger Mother’s old-fashioned discipline. Some of her parenting choices struck me as bordering on child abuse, and, as a brain development scientist, I can hardly recommend her style. Yet Chua was a regular visitor to an important sector in the land of executive function. As I will address later in the book, researchers investigating parenting phenomena have discovered some extraordinary things about a behavioral style called authoritative parenting. It turns out that some of Chua’s technique sailed on the trade winds of good sense.

All Roads Lead to China

Chua’s book brings into consideration another aspect relating to executive function skills in children and adolescents: the important-as-oxygen cultural issues. She acquired her belief in discipline from her parents, immigrants from China, and was regularly exposed to people whose social currency had a tradition of strong academic achievement. What would we find if we measured effortful control in students from countries with such strong, successful traditions?

That work has been done, and the results won’t surprise you. First, the effortful control scores of kids in Asian countries that are broadly considered to be strongly focused on academics are stratospheric. Joining them at altitude are their academic scores; the five top-scoring countries on the international PISA assessments include Shanghai, Hong Kong, Singapore, Japan, and South Korea.
What about the good old USA? Years ago, researcher Larry Steinberg tested impulse control in subjects across the Chinese educational food chain (ages 10–30), comparing them to age-matched controls in the United States. Amazingly, he found no real differences between the results put up by 4th graders (10-year-olds) in the two countries.

Unfortunately, the good news didn’t stay good. Like a slow-moving earthquake, a fissure soon created a gap between the two cultures. By age 14, Chinese kids scored 20 percent higher than their U.S. counterparts; by age 18, it was 45 percent higher. The score differential peaked at age 20, at 50 percent. Does that sound familiar? You might recall the Evel Knievel story that started this chapter. U.S. student scores are competitive with the rest of the world up until 4th grade—then they fall off a cliff.

Another instance of cultural influence on executive function can be found in our country’s immigrant population. A broad mixture of families, many from high-scoring cultures, immigrate to the United States and enroll their children in American schools. Does transplantation affect their kids’ academic performance? Do behavioral differences persist?

The answer, simply put, is that they carry their good stuff with them. Many immigrant kids thrive here—academically, behaviorally, and socially. This is true even in the face of the cultural headwinds immigrants naturally experience when trying to integrate into a new place. The phenomenon is so widespread, and so counterintuitive, it’s been given its own name: the immigrant paradox.

Correlation Is Not Causation

As mentioned, not everybody buys this executive function cheerleading, and I’d like to talk about why.

Did you know that the annual number of Americans who died because they became entangled by their bedsheets correlates
beautifully with the annual total revenue generated by U.S. skiing facilities? Measured between the years 2000 and 2009, the two graphs rise and fall together like twin snakes doing a synchronized swimming routine. Believe it or not, this fact, taken from the terrific website Spurious Correlations, is relevant to our purposes. Here are a few more curious but relevant facts to ponder. The marriage rate in North Carolina correlates (with similar serpentine elegance) with the state’s number of legal executions, whereas the marriage rate in Alabama correlates with the number of people electrocuted by power lines.38

Why bring up such nonsense? Because a lot of the previously described behavioral data, as promising as they seem, remain plagued by correlational disease, which usually has a rocky relationship with causality. This is true with any study of descriptive research. Correlation is not causation, as marriages in the southern United States do not really affect the rate of particular forms of violent death—at least, we hope they don’t.

Correlational data isn’t useless math, of course. Demonstrations of its power come from observing student EF scores and future adult outcomes. You just have to be able to tolerate the strong flavor of complex statistics. And you must follow “kids” for decades, in a canonical longitudinal study. Such studies are both hard and expensive to do. Yet real findings have emerged, including an adult version of the same high-score-good/low-score-bad story. (And to be fair, terrific “intervention” studies have also been done, which we’ll discuss later.) The bottom line is that the predictive relationship between executive function and future outcome remains strong, even as the subjects become AARP-eligible.

**Oversimplification**

As I’ve emphasized, the correlations between strong executive function and positive long-term outcomes last well into
adulthood. Physical appearance was an early, startling finding, especially when subjects were asked to step on their bathroom scales. Students with high EF had lower body mass indices (BMI) as adults, and they kept the weight off in middle age. Their rates of substance abuse, including alcohol, were lower, too. They even had healthier teeth.

High scorers on measures of EF were more empathetic, had more friends, and were less likely to experience psychiatric disorders (especially anxiety and depression). They didn’t get angry very often, and they were less prone to divorce. Such stability was rewarded in the workforce with the ultimate laurel: they earned higher salaries.

The story for low self-regulators was contrastingly depressing. Subjects were more likely to be fat, to abuse alcohol, and to divorce. They got angrier more often, were more prone to domestic violence, and were more likely to be incarcerated—and not at a trivial rate. Greater than 40 percent of the kids with the lowest scores were already scarlet-lettered with a criminal conviction by age 32. (In contrast, only 12 percent of control subjects had convictions by that age.)

It’s easy to want to applaud these findings, but easy to roll your eyes at them, too. They probably deserve neither reaction, though, especially concerning teenagers and their GPAs. Researchers offer many reasons to explain poor academic performance in teens. Some fault parents for not providing challenging learning environments at home. Others fault teachers for not providing the same at school. Some believe teens are bored and lose interest. Others believe boredom is just another word for overindulged laziness. Racial bias exists in the way tests are constructed; similar bias persists in the way school districts are structured.

Cultural issues are messy as well. The United States deals with unique social challenges, from a searing racial history to the “usual suspects” of low socioeconomic status (poverty,
depression, and family fracture come to mind). We’re also the richest country the world has ever seen, making our challenges unlike those of any other nation on Earth. This makes cross-cultural comparisons difficult.

That’s the beauty of the executive function data that have been collected. The cited research has addressed most of these confounders, some in meticulous detail. I’m not shy about keeping complexity in mind—after all, I’m a brain scientist. Yet when the statistical dust settles, what’s left in these data is a clearly understandable problem with a potentially powerful bromide. And executive function research has happily blessed us with one of the valuable traits in all of science: the power of prediction.

Our challenge—which is by no means small—is to understand the teenage brain. Our elixir is the application of brain science. Since students fall off the academic cliff around puberty, understanding what happens under the hood of a typically developing adolescent brain is extremely valuable knowledge that will give us better insight about what happens when things go wrong.

Understanding the problems may even show us the way to fix them—or at least get us started on constructing the bridge we need to span the canyon.
Part II: Why Rational Teens Make Rash Choices

It’s time for a closer examination of how the teen brain looks and how the teen brain grows—to describe the neurobiology behind executive function, and then see how this understanding applies to learning. We’ll consider EF’s adult form and delve into how it got there, and we’ll use a neurological lens to scrutinize the contradictory aspects of adolescent behavior, from the heart-warming to the stupid.

Our discussion starts in New York City, with a description of one of the most controversial shows that MTV ever broadcast. . . .
Brain Structure

The TV program was called *Jackass*. And boy, did the show deserve that title.

For those not familiar with it, MTV’s *Jackass* involved a group of guys doing risky, occasionally life-threatening stunts, all live for the camera. There were many variations, from taking a ride in a limo filled with bees to creating the legendary “poo-cano” (don’t ask). Teenagers loved the show, probably for the same reasons teenagers love unprotected sex and binge drinking.

Adolescents worldwide attempted to reproduce the stunts they watched. They set themselves on fire, leapt out of buildings, and jumped over moving objects. Some died, many more were injured, and a few became parties to lawsuits (the litigants were usually parents).¹ These actions seemed to confirm a pervasive stereotype: teenagers can do really stupid stuff. They make poor, impulsive decisions. They don’t understand the consequences of their behaviors. They become peer-needy thrill seekers. Sounds like their executive function warriors went missing in action.

Statistics seem to bear this assessment out. Teenagers *do* engage in risky behaviors. They take more risks then they
did as younger children, and take more risks than they will as adults. For evidence, look no further than your insurance bill. Automobile insurance premiums are higher for teenagers than for any other group, and highest for teenage boys. That’s because motor vehicle accidents are the leading cause of death in this age group, responsible for half of all teen fatalities. The second and third biggest causes of teen death—homicide and suicide, respectively—are no less alarming or tragic. Researcher BJ Casey puts the risk this way: “The bad news is that during this time, relative to childhood, [a teen’s] chances of dying from putting themselves in harm’s way will increase by 200 percent.”

That’s Not the Whole Story
Given these data, you might feel like putting the teens you care about into a witness protection program until they reach adulthood, just for their own safety. There’s no question that there are lots of examples of scary teenage activity, but it’s important to understand that the age group is not a monolithic entity following a single behavioral path. Research shows that adolescents don’t always choose to be stupid. They are capable rational decisions. Consider this true story of a nonagenarian, a flooded house in southeast Texas, and three alert teens.

Sallie Cole, a 93-year-old grandmother, knew she was in trouble. The rains were coming down in biblical torrents in Kountz, Texas. The water was rising and would soon flood her home. As she lived alone and could only get around using a walker, the situation was shaping up to become a life-threatening one.

Three local teenagers, the medal-worthy heroes of this story, deduced the danger the Sallie faced. Forming a rescue party, they swam to Sallie’s front door and then created a human sedan chair: they locked arms and carried her to safety in style! Once she was in a safe place, they swam back to the house and retrieved her walker.
A grateful Sallie asked if she could offer them payment. They said no. Instead, they left her with their phone numbers, encouraging her to call if flood waters ever threatened again (nearly a sure bet in Southeast Texas). They even volunteered to return to handle clean up once the water subsided. “If you need any yardwork or anything, we’ll be happy to help you,” one said. The trio then spent the rest of the day assisting other people in similar situations.³

This may just be a single example, but it makes a larger point: teens aren’t always jackasses. They are fully capable of making rational, even heroic, choices.

Why, then, don’t they make them more often? The answer has powerful implications for education, and we’ll spend the next two chapters exploring it. I want to start with some background brain facts, though, before embarking on the neurologically-based explanations. That way, if it’s been a while since you took basic biology class, you’ll be better prepared to understand how executive function develops in teens and why that development takes place so unevenly. Along the way, we will discover the difference between Jackass teens and Sallie-rescuing teens—as well as a thing or two about ourselves.

State of Mind

Let’s start our discussion about basic brain biology with a question: if you could magically hold your own adult brain in your own adult hands, what would you think? (Besides, perhaps, wondering how you could see anything at all.)

Most probably, you’d be completely surprised—or maybe grossed out—not by its color (pinkish white, mostly from blood), and perhaps not by its shape (it looks like a big walnut). You’d probably react most strongly to its squishiness. For all its hard-wired complexity, the brain is much softer than almost any meat you’re likely to encounter in, say, a supermarket. If you continue
to hold it for even a few seconds, the brain will start to deform around your fingers, like it’s melting. It’s not melting, of course. But its startling physical vulnerability will hardly make you think you are beholding the most complex computing device the world has ever known.

And yet you are. Your brain is a thinking machine, comfortably floating in a salty hot tub set to a balmy 98.6 degrees Fahrenheit. It’s protected by a biological Fort Knox, with tough tissues surrounded by a rock-hard skull. These layers of protection guard the 86 billion nerve cells crammed into two lopsided hemispheres roughly the size of your two fists, with about 186 million more brain cells on the left side than on the right. And these cells, only about 10 percent of which are really neurons, form more than 60 trillion chatty connections with one another (the other 90 percent are termed glial cells, which, for no good reason, means “glue”). Some neurons have 1,000 connections to other nerve cells, which seems like a lot until you compare them to others, like the ones involved in motor functions, which can have more than 100,000.

Like teenagers in high school, your brain cells and accompanying tissues form extremely active social networks. They also gobble up lots of power. Though your brain is only 2 percent of your body weight, it demands 20 percent of all your energy. It’s got a finicky sweet tooth too, extracting energy only from sugars and leaving fats alone. Cut off the blood supply, which provides both sweets and waste disposal services, and you’re about 10 seconds from loss of consciousness, 2 minutes away from loss of reflex, and 6 minutes away from loss of life.

How can we describe an organ whose complexity rivals that of the U.S. tax code? One way to simplify things is to consider the human brain like a state or province, complete with cities, highways, and geographic features. Many of the original neuroanatomists seized on this analogy, using civic words to name much of
what they identified. There’s a region called the *pons*, Latin for bridge (its discoverer said it reminded him of one). There’s the *fornix*, meaning arch, so named for the same reason. There’s a region called the *cerebral aqueduct*, like the Roman stone equivalents; *cisterns*, meaning reservoirs; and *tectum*, meaning roof.

Geographic features also abound in this heady metaphor. Your brain has *gyri* (ridges), *sulci* (valleys), an *insula* (island), and a *hilum*, which literally means “unimportant thing” (they’re critical, actually, and you have many of them). There’s a group of tissue collectively termed the *limbic system*, which means “border,” based on the idea it looks like the boundary between two neural “counties,” the brain stem and the cerebral structures blossoming above it.⁶

Some areas of the brain are somewhat self-contained regions charged with doling out specific functions; these can be thought of as “cities.” The oldest city is in the center of your brain, sometimes referred to as the “lizard brain” because it functions in lizards the same way it functions in us (looks like a lizard’s brain, too). The newest city (in evolutionary terms) is the region just behind your forehead, the *prefrontal cortex*. You might call this region the human brain, because no other creature has it. Most of the functions that define our species, including critical aspects of executive function, originate here. Figure 2.1 presents a diagram of these areas’ location.

The quaint anatomical terms used for brain components reflect the thinking of the times when they were first identified (generally the late 19th century) more than modern neurological understanding. Some of the biggest changes in our knowledge concern the neural connections between regions, the “highways” linking our metaphorical cities. Many of the brain’s most powerful functions occur along these connections, and there are many to choose from. There are large interstate freeways, smaller state highways, narrow neurological boulevards, and tiny cellular
alleys. The two highways we’ll spend the most time discussing connect the prefrontal cortex with those lizardlike structures near the center of your brain. Interestingly, no two highway systems are exactly the same in any two brains, even those of identical twins. That means that every brain is hooked up differently from every other brain, which has enormous implications for human behavior—especially when we talk about executive function.

**The Brains Behind Executive Function**

Executive function involves reciprocating electrical communications between large areas of the brain, two of which are shown below.

**Limbic Structures**

Responsible for many functions, including the generation of emotional responses, creating and processing memories, and originating "basic" appetites, such as the desire for food and sex.

**Prefrontal Cortex (PFC)**

Human evolution’s "newest" part of the brain. Involved in controlling the appetites of limbic structures as well as decision making, planning, social behaviors, and many cognitive functions considered uniquely "human."
We’ll get to that in moment. Right now, we’re going to take a trip to Disney World!

**Hidden Structures**

Tucked inside a gigantic 18-story geodesic dome, Spaceship Earth is the first attraction you see on entering Walt Disney World’s extraordinary Epcot.

The ride is easily my favorite Disney experience. You’re seated in a car on a slow-moving conveyor belt, embarking on a stately ride through the history of human communication. Spiraling up the dome’s interior, you begin with cave drawings and end with Apple Computers. I’ve been on the ride dozens of times.

On one of those occasions, an annoying malfunction occurred, literally halting the cars in their tracks in the middle of the journey. Mine was parked next to a burning aqueduct scene. Its unpleasant smell remained in my nostrils for hours afterward, but I did get a chance to examine the dome’s interior structure. What I saw was lots of cleverly hidden scaffolding, trusses, metal struts, and reinforcing bars, all designed to support the snaking tracks that carried the cars as they ascended 180 feet through the structure. I have since decided that Spaceship Earth is an ideal illustration of the human brain’s structural interior.

As mentioned, you can divide brain cells into two overarching types, glial cells and neurons. Glial cells, which make up 90 percent of the organ’s cellular population, are like Spaceship Earth’s interior scaffolding. Neurons, which make up the other 10 percent, are like the tracks that spiral through it.

For years, scientists thought glial cells were involved only in unintelligent structural support, providing the cellular corner braces, floor joists, and load-bearing walls for the “thinking parts” of the human brain. Now we know that while they do perform these functions, that’s just their day job. Glia are also nursemaids, sanitation engineers, morticians, and signal processors, playing a role in the care and feeding of neurons, removing
their ever-present molecular garbage, adding to brain health by getting rid of dead cells, and assisting with electrical communications throughout the brain.7

Neurons, however, usually get all the media attention. The typical brain contains 86 billion neurons in a bewildering number of shapes and sizes, though they do have some common structural elements, highlighted in Figure 2.2.

**Basic Neural Anatomy**

*Though neurons come in a wide variety of shapes and sizes, they share basic structures, highlighted in the simplified diagram below.*
One easy way to visualize these elements is to stretch out your arm and inspect it, from fingers to elbow. When you do, you are looking at the general shape of a neuron. Like your forearm, one end of a neuron has lots of branchlike “fingers” called dendrites. The “hand” to which the dendrites connect is the cell body, which contains the nucleus of the cell. The nucleus possesses the neuron’s genetic instructions, complete with cellular command-and-control.

The “arm” connecting the cell body to the neural elbow is the axon. Unlike your flexor-strung appendage, the axon is quite slender and can be long. The longest human axon is the dorsal nerve root ganglia (DNRG), which runs from the base of your spinal column to your big toe, about 3 feet in length. The world-record length for any axon belongs to the blue whale’s DNRG, however, at about 75 feet.

Our arm analogy starts breaking down when we consider the neuronal “elbow,” because this end of the cell doesn’t look anything like an elbow. It’s composed of tiny fingers called telodendria, which are similar to dendrites though smaller in number. Telodendria are chock-full of chemicals termed neurotransmitters, which are critical to the communication abilities of the brain.

These abilities are as electrical as Las Vegas. The neurons that contain the brain’s bustling energy are hooked up in a linear, branching fashion, comprising the circuits necessary to pass along that electrical information. The signal flows from the dendrites (fingers) down through the axon (arm) to the telodendria (elbow)—where they immediately encounter a problem. There’s a gap, a space that must be crossed, between the elbow of one neuron and the fingertip of another. One of the most interesting aspects of the connected world of neural wiring is that it’s not physically connected at all.

This tiny gulf is called a synapse, meaning “joins together,” though it should really be called “joins apart.” Neurons jump this
space using neurotransmitters, the ones stuffed into the teleo-
dendria. Neurotransmitters act like molecular couriers. When
neuron A becomes electrically excited, it spits those couriers
into the space. The molecules make the short commute, bind-
ing to receptor molecules on adjacent neuron B. Very quickly,
neuron B reacts, evidence that information has successfully
traversed the synapse. Sometimes it reacts by getting excited.
Sometimes it reacts by shutting down.8

All of this, of course, is an enormous oversimplification. For
deeper understanding, some other ingredients must be added to
the mix.

**Wire Cutters**

Everyone who’s ever watched an action movie knows the
scenario: there’s a bomb, it’s attached to a timer, and that
timer is counting down the seconds until massive, maybe even
world-ending, destruction. To save the day, the doughty protag-
onist tears open the fearsome weapon’s outer casing to reveal
a mass of colored wires (they’re always colored wires). He (it’s
always a he) pauses, wire cutters in hand. If he clips the right
wire, he defuses the bomb. But which wire is the right wire?

You’ll find a variation of this trope in the final scenes of The
Abyss. The familiar clichés are dutifully present: the action hero
is male, the bomb is atomic, and he must save the world by
cutting a specific color of wire. This time, though, our hero is
a gazillion feet underwater, with only a sickly yellow glow stick
for light. Unfortunately, that glow stick renders all the wires the
same color, which is a problem because one’s black-and-white,
the other yellow-and-blue. Fortunately, the film is directed by
James Cameron, not Ingmar Bergman; the hero guesses right,
and we all live to watch another movie.

Why are those wires colored, anyway? We just discussed
what a standard-issue neuron looks like, but I omitted something
crucial: the outer covering many neurons have around their
axons. This coating is important to our discussion of executive function. To describe it, we need to talk a little bit about electricity and a lot about the reason wires are pigmented.

Electrical wires are usually made of copper, so what’s with all the black and white and yellow and blue? These multicolored coatings around the copper serve two purposes: (1) to help designate specific circuits, and (2) to provide electrical insulation. Obviously, being able to identify wires by color is beneficial, but why do wires need insulation in the first place?

**Insulation Solutions**

Wires are insulated for the same reason you buy winter coats. If it’s cold outside, you wear a coat to keep your vital 98.6 degrees inside your body, recycling its warmth to provide the heat you won’t get from the great outdoors. Similarly, if you don’t slap a coat on the wire, the current will dissipate from the copper into the great outdoors, and the electricity will have a hard time performing any useful function.

Neurons face the same problem. Like their copper colleagues, without insulation, their circuits won’t work well. Neurons have solved this problem in an interesting way. To both visualize and describe how it works, I’d like to bring back my forearm-as-neuron analogy.

Go ahead and stick your arm out again, but this time wrap a towel around your arm several times. That’s an awkward but adequate visualization of how neurons insulate themselves. They possess a type of hand towel, a living cell that wraps around their axons like the cloth around your arm. Brain scientists call this cell an *oligodendrocyte*, a type of glial cell. It performs similar insulating functions, allowing the wrapped-up neuron to conduct electricity efficiently.

The insulating secret sauce inside oligodendrocytes is a biochemical called myelin, a substance made of the same stuff you find in a Snickers bar—fats, salts, and proteins. Myelin is also
colored, if you consider white a color. Because myelin appears grayish-white under the microscope, we term neurons wrapped by oligodendrocytes “white matter.”

Myelin’s insulating properties help neurons deliver signals with as much speed as a Japanese bullet train—a blistering 100 meters per second. In neurons without myelin, the signal travels through neurological molasses, poking along at 1 meter per second. Myelin’s critical function is pointed out by the fact that its erosion results in a devastating disease: the onset of multiple sclerosis.9

Interestingly, you aren’t born with all the myelin you need in your brain. This means you will need to finish brain development outside the womb. It’s an extremely slow process, however: white matter volume doesn’t peak until you get your first AARP letter, about 50 years after birth.10

By the way, the cell body (the “hand” in our arm analogy) isn’t insulated with myelin, so it’s not white. But it still has a color under the microscope, and that color is gray. Unwrapped areas (dendrites, cell bodies, even a few axons) are collectively called “gray matter.” We suddenly have the origins of two neuroanatomical words you’ve probably heard before: white matter and gray matter. Both are significant when it comes to discussing executive function and teen brain development.

Mark Twain and Executive Function

Here’s my favorite Mark Twain quote, which has surprising relevance to our modern understanding of EF and neurons:

When I was a boy of 14, my father was so ignorant I could hardly stand to have the old man around. But when I got to be 21, I was astonished at how much the old man had learned in seven years.

The quote’s meaningful to me not for its breezy irony, but for its not-so-breezy context. These words are not autobiographical.
Twain’s father died when Twain was a boy of 11. Young Samuel L. Clemens left school the next year and went on to receive much of his subsequent education from the University of Public Libraries, where he learned a lot about life—perhaps even about how other boys react to living fathers.

I also like the quote for its rueful surrender to the power of experience. Time, it turns out, is the ripening agent of executive function, a fact that translates into actual brain science. Much of the brain’s physical architecture is shaped by experience through time. We won’t understand how adult EF works until we understand how its cellular fields of gray and white are affected by this shaping, which requires describing two more concepts.

**Concept #1: Deep Specialization**

Brain function is remarkably specialized. Consider the regions responsible for the concept of “animals.” You process the word “giraffe” in regions different from where you process the giraffe’s actual image. If a stroke destroys neural connections between the two, you might be able to write the word giraffe, and even describe one physically, yet you’d be unable to recognize its picture.

Other regions are equally finicky. Some will only respond to straight lines tilted at 45 degrees, no giraffe in sight. Other regions process only 30-degree-tilted lines, not 45-degree ones. One area, the fusiform gyrus, doesn’t do lines at all. It’s specialized for faces, complete with eyes and mouths, and not legs and ski masks. Still other regions process feelings—love, disgust, fear—completely separate from giraffes, tilted lines, and faces.

These regions are as connected to each other as a pyramid scheme, helping us interpret the experiences of life. If you observe a grasshopper leg tilted at 45 degrees, it’s because neurons that recognize the insect start electrically chatting away with neurons responsible for 45-degree-line processing. The combination helps produce the perception.
Emotions are integrated into these combinations, too. Suppose Mark Twain’s dad had lived. If Mr. Clemens walked in the room, Samuel’s 14-year-old brain would recognize him instantly, perhaps with disgust, as his face-processor dialed up his disgust processor and the two started communicating like texting teenagers. Enough experience might weld the connections together. What those patterns look like depends on the type of experience being, well, experienced.11

**Concept #2: Deep Connections**

The neurological wiring diagram bringing these functions together has been unimaginatively christened the connectome. With at least 100 trillion synapses, the connectome is the most complex schematic ever discovered. Its complexity is made worse because much of it is plastic, moving and shifting with the flexibility of a Hogwarts staircase.

Not every region is adaptable, however. Some connections come hardwired at birth, supervising life’s basic “housekeeping” functions. Infants are illustrative. Though controlled by connecting neurons, nobody teaches babies’ brains how to breathe or keep their hearts beating. These schematics are experience-independent.

Other connectome parts are completely free-range, as flexible as ballet dancers, available to learn virtually anything experience throws at them. Almost everything instructors explain at school (and parents explain at home) is processed in these lithe regions of the connectome. In other words, parts of the brain are hardwired not to be hardwired at all; they are experience-dependent.

Some regions are simultaneously hardwired and free-range. Language is a great example. All babies are born with the ability to speak a language (that’s hardwired), but no baby is born with the specific ability to speak Mandarin (that’s free-range). The visual system is another example. Brains actually require photic
experience—meaning they need to see external light—to wire properly. This wiring is experience-expectant.

Some members of this category possess genetic time bombs embedded in their nuclear DNA. These “bombs,” which are really executable neurological programs, won’t go off until a certain amount of time has passed. This can be months, or even years. Puberty’s an excellent example. All hormones and supervising reproductive instructions are programmed into babies at birth, but years will pass before the obnoxious door slamming, eye rolling, moodiness, and other classic manifestations of adolescent drama start. We call such malware “developmental programs.”

Of Gladiators and Brains

I love chariot races in period-piece movies the way some people love chocolate. Or ripped abs. These scenes also provide another convenient way to describe the neurobiology of executive function, the subject to which we now turn.

My first exposure to a chariot race—William Wyler’s classic 1959 Ben-Hur—almost spoiled me for the rest. The second was less impressive, and came in the early scenes of the animated The Prince of Egypt. The third chariot race, another step down (but still awesome, of course), was in the technically challenged Gladiator. All of the chariots in these races have the same three elements: drivers, horses, and the connecting reins allowing the drivers to control the horses (except for Gladiator, where the chariot has a 21st-century gas cylinder attached to its underside, the better to flip it over during a crash; you can see this cylinder easily when the set’s dust settles over the ancient hippodrome). The basic design elements of these vehicles (sans gas cylinder) make a great metaphor for describing the neurobiology of mature executive function: the driver is the prefrontal cortex (PFC), the horses are the “lizard brain,” and the reins are the neurological connections between the two.
The Charioteer

The PFC lies directly behind your forehead and is evolution’s most recent addition to our cognitive pantheon. It’s as huge as Thebes, taking up almost a third of the cerebral footprint and by several measures the largest, most complex brain structure in the animal kingdom.

The reason the PFC is the charioteer-in-chief is because it drives things, including most of the experiences and behaviors filed under the general executive function label. Recall from Chapter 1 that this label comprises a trio of behaviors: response inhibition, cognitive flexibility, and working memory. As we discussed, this behavioral triumvirate can be mixed and matched, wardrobe style, to produce secondary behaviors like planning, attentional control, problem solving, and emotional regulation. Though scientists disagree on exactly what gets mixed and matched to produce what, they all agree control occurs in here. The PFC drives them all.

Neuroanatomically, you can divide the PFC into several provinces, each with its own behavioral boundary. The lateral PFC (roughly the regions behind the sides of your forehead), is involved in memory formation, attention, and timed sequencing of events. The orbitofrontal cortex (the region right behind your eyes) is involved in response inhibition and social/emotional behaviors. The medial PFC (the region roughly at the crown of your forehead) is involved in conflict resolution, social status updates, and attentional states too, particularly if a task is challenging. Taken as a whole, the PFC consists of distinct regions, modular in design, each section exerting regulatory responsibility over specific behaviors.14

Whether these regions mediate the assigned behaviors outright or are the result of consulting connections is under active investigation. We do know that unusual behaviors arise if you damage the PFC. People can become apathetic. Personalities can change. One famous case from neurological textbooks involves
19th-century railroad construction worker Phineas Gage. An explosion on the job drove a tamping iron through his brain, damaging large regions of the frontal lobe and its connections. Miraculously, Gage survived, but with a personality dramatically altered. The well-liked, responsible worker was transformed into a “fitful, irreverent, indulging” man who was “no longer Gage”—and was soon unemployed.15

The Horses

If the PFC is the supervising charioteer, what exactly is the organ trying to manage? Just what a normal chariot-driver manages—the horses, the second component of our metaphor. These behavioral wild stallions lie in the middle of our brain, at the very top of where our spinal cords enter our skulls. This summit goes by lots of names, including “lizard brain” or “reptilian brain,” because it functions in us as it functions in lizards and other reptiles. It’s the source of our most primitive, violent, “animalistic” emotions.

For all their fierceness and lust, these primitive regions look surprisingly tame, even confectionary—like a benign Tootsie Pop, with an inner core and hard outer shell. The inner core is actually just a swollen region of the spinal cord. It’s an important protuberance though, controlling things like breathing, swallowing, heart rate, and blood circulation.16

Ballooning above this bulge, and partially surrounding it, is a shell-like group of structures collectively termed the limbic system. This system includes regions like the hypothalamus, which controls what behaviorists term “the four Fs”: feeding, fighting, fleeing and . . . having sex. The system includes the amygdala, which generates and remembers most of the emotions we identify as passions.17

Without constraint, these furious appetites would rule our lives, mostly to our detriment. The concept of second-degree murder—an unpremeditated crime of passion—occurs in recognition
that some people’s wild horses break their connections, then run roughshod over our legal system. The PFCs of these so-called affective murderers don’t regulate their lizard brains very well. This means they have a hard time controlling aggressive impulses. It doesn’t excuse the crime, of course, but it does underscore the power executive function plays in supposedly civilized society. Interestingly, and perhaps most frighteningly, premeditated murderers have PFCs that bring their internal reptiles to heel just fine; they are the scariest people on Earth.18

The Power of the Reins

Connecting the dots between passion and reason is the job of the third component of our analogy: the reins drivers use to control their horses. These connections play the ultimate role in relaying what our rational brains want to say to their irrational cousins. This neurological conversation affects many sectors of our society besides criminal justice. One form even shows up in game shows. The venerable and still-popular TV program Let’s Make a Deal is oddly similar to an experimental system we use in the lab all the time.

Let’s Make a Deal is an over-the-top, frothing-at-the-mouth game show that asks selected contestants to make choices about potentially valuable merchandise. Audience members, festooned in wild costumes, are shown something of worth. They can either keep what they have or trade it in for a (usually obscured) mystery object. The item may be of greater value, like a car; or of lesser value, like a toaster; or in some cases, a gag gift called a “zonk.” One famous zonk was a 1965 Volkswagen van dressed to look like a monster, complete with a long red tongue that emerged from its grating with the press of a dashboard button. The appeal of the show is to watch the contestants grapple with perilous bird-in-the-hand-type choices.19

This might be hard to believe, but behaviorists use something like Let’s Make a Deal when measuring aspects of executive
function: an experimental protocol called *temporal discounting*. Variations exist, but all involve game show–like options: subjects can choose between taking a small reward immediately or waiting varying lengths of time to receive a larger reward. Unlike the game show, subjects usually know the value of the bigger prize. Whether they’re willing to wait for it is the question, making the experiment a measure of impulse control. That’s squarely in the wheelhouse of people who study communications between PFC and the limbic structures, the reins of our chariot analogy.

It’s tough work. Like a successful Hollywood agent, the PFC’s power comes from its connections. Progress has been made understanding the region’s complex circuitry, thanks especially to noninvasive imaging techniques. Researchers now know the PFC has three overall classes of connections between it and the rest of the brain (relevant to EF). The first deals with attentional states, the second with stress responses, and the third with general emotional reactivity. Each represents reciprocating two-way conduits in the adult brain, whereby information flows from head to heart and back again. Somehow, responsible behaviors emerge.²⁰

Of course, this is a substantial oversimplification, as I frequently explain whenever discussing the rickety bridge between brains and behaviors. To illustrate why I so often choose to oversimplify, let’s look at what happens when I *unsimplify*, just this once. Below, in italics, find a thoroughly detailed (and thoroughly uninterpreted) description of the neurobiology behind an EF-related behavior: age-related changes in brain activity associated with typical temporal discounting.

Ready?

*Maturaing impulse control is associated with changes in ventromedial prefrontal cortex activation in concert with alterations in the activation of the posterior parietal cortex, anterior cingulate cortex, ventral striatum, insula, and inferior temporal gyrus. Impulsivity decreases are*
also associated with alterations in limbic frontostriatal activity, involving networks of neurons associated with inferior parietal cortex, dorsolateral prefrontal cortex, and other less-specified subcortical areas.21

Got all that? These are the “reins,” dressed in their finest—and most obscure—brain science linen, illustrating just how complex these “reins” can be, even for simple behaviors. Very compelling to a neurobiologist, but hardly a simple affair, which is why this work is so hard to do well.

And it’s about to get more complicated. You may not know this, but so far we’ve limited our discussion mostly to normalized healthy adult Western brains, primarily those of college students and primarily male. Most brain scientists do. Before we leave the topic and get into their teenaged siblings, we have a few confounders to address.

**Biased Biology**

It’s weird to settle in to read a research paper and find yourself chuckling while your entire profession is being marched out to the woodshed. In this case, researchers were taking the entire behavioral research universe to task because of statistical bias in their choice of experimental subjects.

For economic reasons, researchers usually use the cheapest source of experimental subjects available to them: college undergraduates. The subjects are often American (the United States spends more research dollars than any other country), male, relatively well-off financially even when shackled with debt (especially compared to age-matched kids in developing nations), and often white. Detecting bias, the article called our experimental backstops the WEIRDS, short for Western, educated, industrialized, rich, and democratic. The woodshed-escorting data were well reasoned; being clever enough to couch its acrostic in pejorative terms produced the chuckle.22
The article makes a knife-sharp point. WEIRD kids aren’t representative samples of the total hominid experience. Yet we’ll often make pronouncements drawn from our research as if they pertain to the entire human condition, even when all we have to go on are narrow slices of North America.

This is especially hazardous if you consider that the brain has circuit diagrams wired not by nature but by environment. Remember that experience-dependent category we described previously? Brain circuitry isn’t always permanently soldered to our neurological motherboards at birth.

This warning certainly applies to executive function research. We know economic conditions can rewire EF’s neural substrates, often creating circuits unfriendly to standardized tests. Ditto with stress. And income. A brain might thrive under middle-class conditions, but take that same brain and push its owner below the poverty line, and thriving may not occur at all. The PFC and its relationship to limbic structures are surprisingly vulnerable to how much money you make. We won’t explore such confounders further in these pages, but socioeconomic conditions are a legitimate brain issue. It’s important to keep all of this in mind—literally.  

Similar thin-ice warnings apply to sex- and gender-related issues. We’re only beginning to understand how people’s place on the gender continuum affects their brain development, or even adult physiology. Here’s one embarrassing, fairly recent example: men’s and women’s brains don’t necessarily react to the same drugs identically. That’s crucial when formulating, say, medications that keep you from committing suicide. From a sex-based perspective, psychiatric disorders are unevenly represented too. Schizophrenia is statistically male-heavy, for example, and so is ADHD. Major depression is female-heavy, as is anorexia. These aren’t trivial findings. As we’ll discover, the age of onset for most mental health issues is puberty—and EF plays a central role in many of them.
So, what are we going to do? Since this is a book about science, we have to go where the research dollars have given us streetlights, even if the only view we have is WEIRD. We need to keep these confounders in mind, however, even when it forces us to view certain findings with a great big boulder of salt.

**Where We Go Next**

I once had a front-row seat to a German protest. I was in Hamburg to deliver a guest lecture, sitting on a street-side bench, eating a sandwich. Suddenly, I heard boisterous noises. A student protest was assembling, and the street filled with young people carrying their signs, anger, and indignation. The students became loud and raucous and mildly threatening. Police looked on from the sidelines, vigilant and also mildly threatening.

Like a comet, the crowd soon whooshed past my bench, a gathering ball of noise with a long tail of stragglers, and disappeared around a corner. They were well behaved, fortunately. Minutes later, I noticed one last student, wandering alone with his sign, disorganized and lost. He was intermittently shouting slogans, trying to find his colleagues. The young man began to bristle when he spied a policeman walking towards him. As a lifelong university denizen who has seen many a student protest, I felt sure I was about to see an arrest. Instead, the cop, who was obviously older, touched the young man’s shoulder. Smiling slightly, he pointed out to the student where the comet had gone. The young man still gripped his sign hard, but he stopped shouting. He took off in the indicated direction, turned the corner, and disappeared.

The total elapsed time of the incident was maybe 30 seconds, but it spoke volumes to me. Here were two people, one younger, one older, on opposite sides of just about everything in life, including executive function. The teenager had yet to fully develop what many people call maturity and brain
scientists might call impulse control—something the older cop had acquired years ago.

We’ve spent a long time on the cop’s side of the brain, talking about his PFC and its mature connections to his lizard brain. Now we need to spend some time with the protestor, whose brain was still in training. Remember, we are trying to solve a mystery—why do some teens act like *Jackass* extras and some act like saints? As long as we keep in mind the confounders just mentioned, there’s lots of interesting ground to cover.
About the Author

Dr. John J. Medina is a developmental molecular biologist with special research interests in the isolation and characterization of genes involved in human brain development and the genetics of psychiatric disorders. Medina has spent most of his professional life as an analytical research consultant, working primarily in the biotechnology and pharmaceutical industries on research issues related to mental health. He holds an affiliate faculty appointment at the University of Washington School of Medicine in its department of bioengineering, where he has been named Outstanding Faculty of the Year at the College of Engineering, the Merrill Dow/Continuing Medical Education National Teacher of the Year, and twice, the Bioengineering Student Association Teacher of the Year.

Medina was the founding director of the Talaris Research Institute, a Seattle-based research center originally focused on how infants encode and process information at the cognitive, cellular, and molecular levels. Medina’s books include the *New York Times* best-seller *Brain Rules*, the national best-seller *Brain*...
Rules for Baby, Brain Rules for Aging Well, The Clock of Ages, Depression, What You Need to Know About Alzheimer’s, The Outer Limits of Life, Uncovering the Mystery of AIDS, The Genetic Inferno, and Of Serotonin, Dopamine and Antipsychotic Medications. He has produced numerous courses on brain function, including a 24-lecture set for The Great Courses Company called Your Best Brain. He has also worked as a consultant to the Education Commission and speaks regularly on the relationship between cognitive neuroscience and education.