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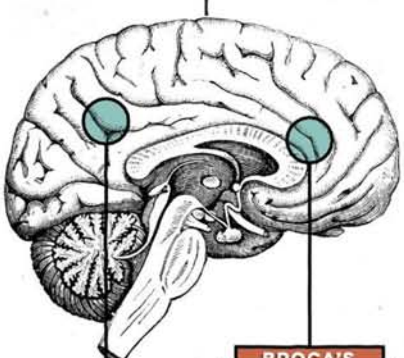

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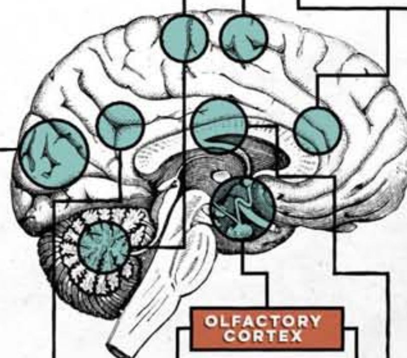

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Emotions Help Steer Students' Learning, Studies Find

Scholar sees passion as mind's 'rudder'

By Sarah D. Sparks   April 26, 2016

Despite what Star Trek's Mr. Spock would have you think, emotions are not the enemy of reason. Rather, new research suggests emotions underpin how students learn in the classroom.

"People think of emotion getting in the way of cognition, but it doesn't. Emotion steers our thinking; it's the rudder that directs our mind and organizes what we need to do," said Mary Helen Immordino-Yang, an associate professor of education, psychology, and neuroscience at the University of Southern California, in an interview with *Education Week*.

In a new book, ***Emotions, Learning, and the Brain***, Immordino-Yang and her colleagues at USC's Brain Creativity Institute found that as students learn new rules during a task, such as the most efficient way to answer a math problem or the best deck to choose in a card game, they show emotional and physical responses long before they became consciously aware of the rules or are able to articulate them.

Gut Check

This emotional response—think of a student having a "gut feeling" that a particular answer was right—was the first sign of a student learning from her experience with the task. In fact, separate studies found that people with a particular type of brain damage—to a part of the brain that connects areas associated with feeling emotions with those associated with developing cognitive strategies—do not learn from failure and continue to choose inappropriate strategies for solving a problem even if they consciously "know" the rules.

"What happens when thinking is devoid of emotion is you don't remember it or think deeply about it," Immordino-Yang said.

In a classroom context, Immordino-Yang said, that means students who feel no meaningful emotional connection to the material they learn will have a harder time both remembering and applying it.

While educators have long discussed the role of music or art in engaging students emotionally with learning, Immordino-Yang and her colleagues have found that even abstract academic concepts can inspire an emotional connection if people understand their context. For example, mathematicians show the same pleasure response in the brain when they see an efficient equation as others have shown when viewing a beautiful piece of art.

"The ability to feel passionate about something is a skill. What we need to teach kids is that feeling passionate about something doesn't just fall into your lap," said Immordino-Yang. Rather, students can learn how to take interest in subjects that aren't immediately entertaining.

By the same token, separate studies help endorse Mr. Spock's point of view: They suggest that negative emotions can interfere with learning in part because they compete with normal engagement with new concepts.

Feedback Cycles

As important as emotion seems to be for learning, schools may not do enough to support students' emotional development as a tool for learning, some experts argue. Prior studies have shown children become less positive over the course of elementary school, and new German studies suggest academic engagement and achievement—or the lack of them—could create feedback loops for young students.

Stephanie Lichtenfeld, a senior psychology lecturer at the University of Munich, tracked 520 students in 31 schools from the beginning of 2nd grade through the end of 4th grade. She recorded the students' levels of enjoyment, anxiety, and boredom in math classes, as well as their end-of-year math-achievement levels.

"The emotional pattern gets increasingly negative over the school years," Lichtenfeld said. "Enjoyment really drops over elementary school years, and negative emotions like test anxiety and boredom increase."

Why? Lichtenfeld found each of the emotions **created a feedback loop with academic achievement**. A student who was anxious in math class in 2nd grade was likelier to have lower math achievement at the end of the year; lower math achievement at the end of 2nd grade made it likelier that the student would be even more anxious in 3rd grade, increasing the risk of even lower math performance, and so on through elementary school. Boredom also produced a negative cycle, while early enjoyment in math created a positive feedback cycle.

"These built on themselves over time," Lichtenfeld said during a symposium on emotion at the American Educational Research Association meeting in Washington this month. "That's really a pattern where we should think about interventions to make students feel better in school" in the early grades as a way to improve performance.

Moreover, in a separate German study also presented at the meeting, Philipp Forster of the Ludwig Maximillian University in Munich, found negative emotions can spread among classmates in school.

Forster and his colleagues tracked 411 students in 16 high school math classes in Bavaria. Through surveys, the researcher identified which students were friends and also profiled each student's levels of school engagement, motivation, achievement, and disruptive behavior.

While students did not initially select friends with the same personality

profiles, Forster found that students' **negative emotions—anger, anxiety, and hopelessness—became more similar to those of their friends over time**. By contrast, students did not seem to become more like their friends in positive emotions like enjoyment or pride.

Immordino-Yang recommended four strategies for teachers to improve students' emotional basis for learning:

• Give students open-ended problems that force them to dig into the definition of the task itself.

• Encourage students to recognize and use their own academic "intuitions" while learning—for example, to notice when they feel uneasy about an answer and look back later to see if it was incorrect.

• When trying to improve students' emotions in the classroom, focus on adding meaning to content the students are working with, rather than positive distractions, like telling a joke or giving prizes.

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Published in Print: April 27, 2016, as **Emotion May Be Key Driver of Learning, Studies Show**

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My Family, My Science

One girl's scientific coming of age.

by Hope Jahren

EXCERPT

Over the years I have built three laboratories from scratch, given warmth and life to three empty rooms, each one bigger and better than the last. My current laboratory is almost perfect—located in balmy Honolulu and housed within a magnificent building that is frequently crowned by rainbows and surrounded by hibiscus flowers in constant bloom—but somehow I know that I will never stop building and wanting more. My laboratory is not "room T309," as stated on my university's blueprints; it is "the Jahren Laboratory" and it always will be, no matter where it is located. It bears my name because it is my home.

My laboratory is a place where the lights are always on. My laboratory has no windows, but it needs none. It is self-contained. It is its own world. My lab is both private and familiar, populated by a small number of people who know one another well. My lab is the place where I put my brain out on my fingers and I do things. My lab is a place where I move. I stand, walk, sit, fetch, carry, climb, and crawl. My lab is a place where it's just as well that I can't sleep, because there are so many things to do in the world besides that. My lab is a place where it matters if I get hurt. There are warnings and rules designed to protect me. I wear gloves, glasses, and closed-toed shoes to shield myself against disastrous mistakes. In my lab, whatever I need is greatly outbalanced by what I have. The drawers are packed full with items that might come in handy. Every object in my lab—no matter how small or misshapen—exists for a reason, even if its purpose has not yet been found.

My lab is a place where my guilt over what I haven't done is supplanted by all of the things that I am getting done. My uncalled parents, unpaid credit cards, unwashed dishes, and unshaved legs pale in comparison to the noble breakthrough under pursuit. My lab is a place where I can be the child that I still am. It is the place where I play with my best friend. I can laugh in my lab and be ridiculous. I can work all night to analyze a rock that's 100 million years old, because I need to know what it's made of before morning. All the baffling things that arrived unwelcome with adulthood—tax returns and car insurance and Pap smears—none of them matter when I am in the lab. There is no phone and so it doesn't hurt when someone doesn't call me. The door is locked and I know everyone who has a key. Because the outside world cannot come into the lab, the lab has become the place where I can be the real me.

My laboratory is like a church because it is where I figure out what I believe. The machines drone a gathering hymn as I enter. I know whom I'll probably see, and I know how they'll probably act. I know there'll be silence; I know there'll be music, a time to greet my friends, and a time to leave others to their contemplation. There are rituals that I follow, some I understand and some I don't. Elevated to my best self, I strive to do each task correctly. My lab is a place to go on sacred days, as is a church. On holidays, when the rest of the world is closed, my lab is open. My lab is a refuge and an asylum. It is my retreat from the professional battlefield; it is the place where I coolly examine my wounds and repair my armor. And, just like church, because I grew up in it, it is not something from which I can ever really walk away.

My laboratory is a place where I write. I have become proficient at producing a rare species of prose capable of distilling 10 years of work by five people into six published pages, written in a language that very few people can read and that no one ever speaks. This writing relates the details of my work with the precision of a laser scalpel, but its streamlined beauty is a type of artifice, a size-zero mannequin designed to showcase the glory of a dress that would be much less perfect on any real person. My papers do not display the footnotes that they have earned, the table of data that required painstaking months to redo when a graduate student quit, sneering on her way out that she didn't want a life like mine. The paragraph that took five hours to write while riding on a plane, stunned with grief, flying to a funeral that I couldn't believe was happening. The early draft that my toddler covered in crayon and applesauce while it was still warm from the printer.

Although my publications contain meticulous details of the plants that did grow, the runs that went smoothly, and the data that materialized, they perpetrate a disrespectful amnesia against the entire gardens that rotted in fungus and dismay, the electrical signals that refused to stabilize, and the printer ink cartridges that we secured late at night through nefarious means. I know damn well that if there had been a way to get to success without traveling through disaster someone would have already done it and thus rendered the experiments unnecessary, but there's still no journal where I can tell the story of how my science is done with both the heart and the hands.

Eventually 8 a.m. rolls around, the chemicals need to be restocked, the paychecks need to be cut, the plane tickets need to be bought, and so I've lowered my head and written yet another scientific report while the pain, pride, regret, fear, love, and longing have built up deep in my throat unspoken. Working in a lab for 20 years has left me with two stories: the one that I have to write, and the one that I want to.

Flow:

A strong sense of being creatively engaged – as happens in a close conversation and when reading or watching a fiction – is of becoming one with what we are doing, or reading, or watching. An important researcher on this sense of engagement, which he identifies with creativity, is Mihaly Csikszentmihalyi who has written: " Creativity is a central source of meaning in our lives [because] when we are involved in it, we feel that we are living more fully than during the rest of life ". With a colleague, Csikszentmihalyi used a method in which he gave adolescents signals at random moments during the day, and asked them to say what they were doing and what their emotions were at that moment. Among the findings was that although adolescents spend a good deal of time watching television, they do it more or less to pass the time, and it ' s generally experienced as not particularly enjoyable. Enjoyment is based on experiences that Csikszentmihalyi calls " flow. "

The Experience of Emotion in Fiction:

When we read fiction or watch drama we want to be moved. When we read a piece of non-fiction, perhaps about genetics or history, we want to be informed. At least that's a first thought. It 's not a complete thought because we also often feel involved and moved when we read non-fiction. So let me see if I can put this intuition better. In fiction, as well as in genres like biography, emotions are critical; **we engage with issues because they are emotionally important to us,** having to do with people, with intentions, and with outcomes. The emotions we experience are not primarily those of the characters, they are our own, in the contexts we imagine. In non-fiction, the issues with which we engage may include people, intentions, and outcomes but they can be more various, and need not have our own emotions at the center.

How do we understand emotion? There is fair agreement in psychology that it is typically a process in which some event or person (in the outer world) is related to a concern or a purpose (which is inward). **Emotion is that process in life by which events become meaningful to us. Often it brings the events to consciousness.**

Perhaps the principal reason why emotion is so important to fiction is that it is the touchstone of consciousness. By externalizing certain elements of mind into a book or other kind of object in the outside world – which is what art does – a growth of feeling and consciousness is enabled, both in the author and in the person who engages with the created artwork. As Susanne Langer has put it:

> The emergence of . . . " feeling " in the broadest sense, or consciousness . . . [was] a crisis in natural history as great as the emergence of life from physicochemical processes; the . . . crisis may not have been a " crisis " in the ordinary sense of a single, more or less cataclysmic, event, but a vastly distributed, protracted process taking eons to develop. As it did so, however, " life " in another than physical sense originated with it – " life " as the realm of value. For value exists only where there is consciousness. Where nothing ever is felt, nothing matters.

Fiction has been often thought of as a creation of the writer. Really it 's a joint creation of writer and reader (or viewer), the joint creation of an imaginary, but conscious, world that has emotion (or feeling in Langer's sense) at its center. Emotion in human beings is that process in which events are related to purposes and hence to meanings. What a writer does is to offer cues, or suggestions, so that the reader or viewer can start up and sustain scenes in imagination, and experience for him - or her - self meaningful emotional effects of their juxtapositions.

Memory and Retention

Memories of those who read the narrative, as compared with the expository version, were significantly more vivid, and more often involved the reader as actor or observer in a detailed scene, rather than being reports of events or semantic memories. Narrative, the native mode of prose fiction, can prompt vivid images.

A term that has come into use in relation to getting lost in a book is " transportation. " According to Melanie Green and Tim Brock, transportation is a state of immersion in a story. It can involve the experience that Csikszentmihalyi calls " **flow** " of being totally engaged in what one is doing. It **involves attention, imagery, and emotion**. Green and Brock found that the extent of our transportation into a narrative world predicted the extent to which readers ' beliefs became consistent with beliefs and evaluations in the story.

Green has also found that labeling a story as fact or fiction had no effect on the extent of transportation that occurs.

In researching other effects of narratives, Terre Satterfield and her colleagues offered people the same information about effects of a planned hydroelectric system on a river's salmon population in either a narrative or a didactic format. They found that **people who received the information in a narrative format were better able to evaluate the issues, and better able to apply what they had learned in a complex policy judgment.**

Creative Nonfiction

Creative nonfiction tells a story using facts, but uses many of the techniques of fiction for its compelling qualities and emotional vibrancy. Creative nonfiction doesn't just report facts, it delivers facts in ways that move the reader toward a deeper understanding of a topic. Creative nonfiction requires the skills of the storyteller and the research ability of the conscientious reporter. Writers of creative nonfiction must become instant authorities on the subject of their articles or books. They must not only understand the facts and report them using quotes by authorities, they must also see beyond them to discover their underlying meaning, and they must dramatize that meaning in an interesting, evocative, informative way—just as a good teacher does.

When you write nonfiction, you are, in effect, teaching the reader. Research into how we learn shows that we learn best when we are simultaneously entertained—when there is pleasure in the learning. Other research shows that our most lasting memories are those wrapped in emotional overtones. Creative nonfiction writers inform their readers by making the reading experience vivid, emotionally compelling, and enjoyable while sticking to the facts.

Telling the "Whole Truth"

Emotions inform our understanding all the time. So, to tell the whole truth about most situations that involve people (and most situations do), in the words of Tom Wolfe, we need to "excite the reader both intellectually and emotionally."

The best nonfiction writers do not tell us how we should think about something, how we should feel about it, nor what emotions should be aroused. They simply present the concrete details. The reader's brain, to the extent it has experienced or known something about an exact or similar situation, will be "excited" and the old emotion reexperienced. This squares with what cognitive scientists believe happens in the brain when an experience is about to be stored in the memory. Apparently, various details about the experience are stored along with details of similar, associated, past experiences. When any detail is experienced in the future, the potential for the entire past experience (or experiences) to be recalled is there, including the emotions surrounding the earlier experience. Even the most conscientious and intelligent reader may soon forget the factual content of a piece if the material entered the brain with little emotion wrapped around it. Cognitive research indicates that humans remember best what enters the brain in an envelope of "emotion." If it is true that facts and details are stored along with attendant emotions in a system of cross-files throughout the brain, we writers must recognize it and use it to our advantage.

By "emotion," cognitive scientists mean those feelings we might normally think of as emotions, but they also mean expressions that *imply* emotion—expressions like "terrifyingly hot," rather than "200 degrees Celsius." Unless the precise figure of 200 degrees Celsius (as distinct from 199 degrees Celsius) is significant for the intended reader, "terrifyingly hot" will have more emotional meaning and thus remain longer in the mind.

Too much academic writing ignores this fact, the fact that we humans have not evolved very far from our lower animal predecessors, and thus learn (remember) best any emotion-laden images. In their attempts at objectivity and precision, some of these nonfiction writers think they must avoid interpretive words like "terrifyingly." After all, they reason, to whom is it terrifyingly hot? Not to the scientist, certainly. He or she doesn't think of being terrified by the heat of the autoclave or the molten metal, but is concerned only with recording precisely the temperature observed. If the scientist then writes an article for people unfamiliar with the heat of molten metals, or a nonscientific audience, "terrifyingly hot" will make the point more quickly and even more memorably—the twin goals of such nonfiction writing.

To help a reader fully understand an experience we're writing about, it's necessary to stimulate as many associated memories as possible. Details not only conjure up old memories, they enable us to understand the new idea. We've all experienced the difficulty of communicating a new idea to someone of limited experience. By contrast, it's easy to talk with someone with related past experiences, regardless of their possibly indirect relevance to the one now under discussion. Such a person can take a little something from each of a number of experiences and make them relevant to the present one. This also explains the strength of the metaphor. Of a metaphor, the reader says, in effect, "Oh, I understand…this is the same thing I saw (heard/felt/smelled/experienced) back then. It's not exactly the same, but I can understand better now that I've been reminded of what this is like."

Filling in the Blanks

Dr. Loren Eiseley wrote about anthropology and other sciences so that the well-educated nonspecialists could understand him. Like Dr. Lewis Thomas, the medical researcher, Eiseley wrote clearly and persuasively about sophisticated topics. These eminent scholars were able to go beyond so-called sophistication and come back to what I consider true sophistication—writing that's clear, interesting, witty, and graceful. They usually wrote on serious topics which, in other hands, might put the reader to sleep. In the following excerpt from his book *The Night Country,* Eiseley writes about the elderly poor and ill who live in the railroad terminals of many major cities. He compares them to dying old brown wasps he's observed in midwinter. Like them, these old folks prefer to die in the center of things, not somewhere in lonely isolation.

> Now and then they sleep, their old gray heads resting with painful awkwardness on the backs of thebenches. Also they are not at rest. For an hour they may sleep in the gasping exhaustion of the ill-nourished and aged who have to walk in the night. Then a policeman comes by on his rounds and nudges them upright. “You can’t sleep here,” he growls.
>
> A strange ritual then begins. An old man is difficult to waken. After a muttered conversation the policeman presses a coin in his hand and passes fiercely along the benches prodding and gesturing toward the door. In his wake, like birds rising and settling behind the passage of a farmer through a cornfield, the men totter up, move a few paces and subside once more upon the benches.
>
> One man, after a slight, apologetic lurch, does not move at all. Tubercularly thin, he sleeps on steadily. The policeman does not look back. To him, too, this has become a ritual. He will not have to notice it again officially for another hour. Once in a while one of the sleepers will not awake. Like the brown wasps, he will have had his wish to die in the great droning center of the hive rather than in some lonely room….

Perhaps the most important point to take from this particular image of group life is that Eiseley does not lecture us about the plight of these poor, feeble old folks. He simply paints for us a realistic (though impressionistic) picture of the policeman making his round, and the responses (and nonresponses) of those who huddle on those hard benches. Because he doesn’t clutter up his writing with excess words, we can see the gray old heads tilted back against the hard benches, mouths forced open. Not that he supplied those open mouths—I did. As a reader, I brought to his simple, clear image something from my memories of seeing folks just like these in Grand Central Station. Had he put in many descriptive words, as some writers are prone to do, I wonder whether I’d have supplied that associated memory.

When too much description is presented the reader, he or she thinks, subconsciously, that it’s all there—no other details are needed. Our brains enjoy filling in details—it’s a primitive form of problem solving. Our brains are made to solve problems, and they’ll do it when given the least encouragement. We can give that encouragement by providing a minimum of (carefully selected) information.

Have you ever noticed how attractive a photograph can be of a person’s face seen through a rain-streaked, misty window? We like it because we get to create—we fill in the missing information about the face and experience joy in doing so.

UNDERSTANDING CONFIRMATION BIAS

BY NICKY CASE

Why do people usually only see evidence that confirms what they already believe?

Why do attempts to correct myths sometimes lead to a "backfire effect"?

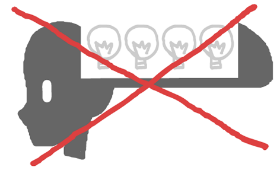
Why does more knowledge make people *more* polarized, not less?

To understand all this, let's think of people's beliefs as a bunch of

JIGSAW PIECES.

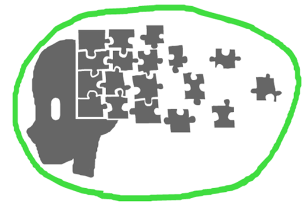
1/4

Most of us think knowledge is passively stored, for later retrieval, like standalone files in a file drawer.

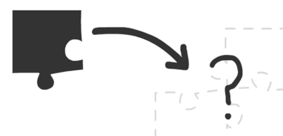


This is wrong.

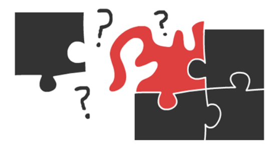
According to psychologist John Dewey, knowledge isn't passively stored, it's actively **constructed** – ideas need to *build off* and *connect to* each other... like a jigsaw puzzle!



So if a new idea doesn't fit in someone's mind, it may not be that they're "wilfully ignorant", but perhaps:



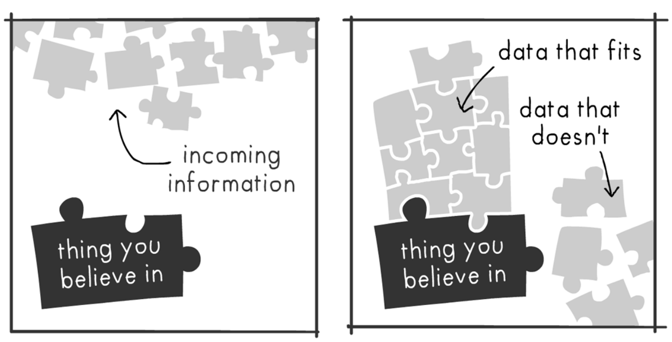
the required connecting pieces are missing...



...or there's a wrong piece already there!

2/4

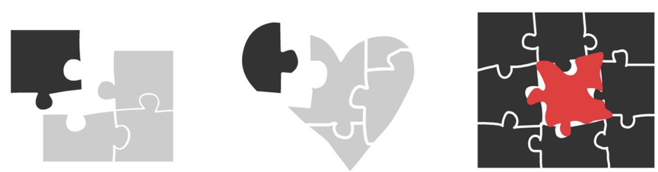
This is why "confirmation bias" exists – we can only take in new pieces we're already ready to connect. Anything we can't, we dismiss as garbage: hence the "backfire effect". Add these two together, and that's why more knowledge makes people more polarized.



Therefore, to effectively change someone's mind, you must **first seek to truly understand them** – to not see them as just "stupid" or "evil", but to see how they fit the puzzle pieces together in their mind.

3/4

Only then, can you...



give them the missing pieces they need to learn something

connect your ideas to their values & interests

show why their old pieces don't fit as well as they thought

But above all, **BE HUMBLE & BE PATIENT.** Putting together a puzzle is hard, and all of us will screw up at some point. Be open. Who knows, the person you're trying to change just may have the puzzle piece that *you're* missing.

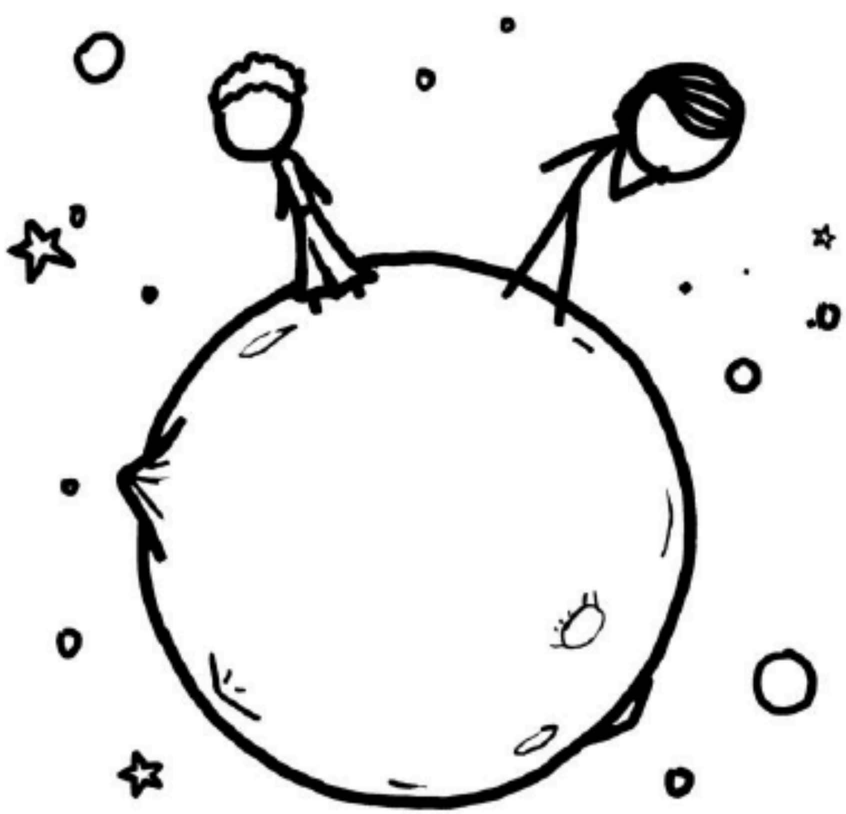
♥, **Nicky** (@ncasenmare)

END

HTTP://BLOG.NCASE.ME/JIGSAW-PUZZLES/

How Long Does It Take to Get to Tatooine?

Maria Konnikova September 18, 2014



On an early autumn morning in 2009, Randall Munroe, a NASA physicist turned full-time cartoonist, was teaching a weekend physics class to high-school students in Cambridge, Massachusetts. The course was part of an M.I.T. program designed to introduce students to topics ranging from sculpture and ancient Greek to geoengineering. Though Munroe's lecture that day had the lively title "Solar Panels, Hand Grenades, and Blowing Up the Moon: How to Think About Energy," for the first hour and a half he adhered to a fairly standard lecture format. What is energy? What can it do? How do you know how much you have?

The students reacted as, well, typical students. "They seemed pretty bored," Munroe recalled. "I could tell, because I remembered being that bored student." Maybe, he joked, one of them had even begun doodling—his own preferred method for passing time when he was in school, and a habit that would later evolve into his popular online cartoon strip "xkcd."

Halfway through his lecture, Munroe decided to shift tactics. Veering away from the traditional classroom approach, he began illustrating concepts with zany examples. What if, for instance, the students had to sort out the energy dynamics of a scene in "Star Wars" or "The Lord of the Rings"? "Suddenly, the kids were excited and engaged," he told me. "Before I knew it, they were running ahead of me, coming up with their own examples and solving their own equations." At that moment, he realized that formulating exciting, relevant questions—questions that stemmed from students' own concerns and interests, however far removed from a lecture hall—might sometimes be the best way to help people understand disciplines as complex as physics. However absurd and hypothetical, such questions seemed to engage students' minds in a way that simple formulas alone did not.

* * *

When we attempt to learn something new, our level of interest in the material is one of the best indicators of how successful we will be. If we are bored by calculus, muddling through on a combination of memorization, technique, and brutal willpower, we may well end up earning the exact same grade as someone who sees the equations as beautiful illustrations of how the world works. But ask us five years—or even five months—down the line to tackle a problem or explain a concept, and those of us who lacked genuine interest will be far more likely to draw a blank than the truly curious. Interest not only makes us more attentive and focussed but also seems to increase the cognitive resources we bring to a subject: we throw much more brainpower at problems that intrigue us than at those that don't. But what is it that creates interest to begin with?

For a long time, researchers believed that interest was relatively stable. Some people were simply more drawn to certain topics than to others: you either loved physics or didn't much care for it, and, while a good teacher could perhaps pique your interest, she couldn't change your underlying disposition in the long run. (Your disposition could, though, be influenced by other aspects of your personality: some people, for instance, were broadly curious and engaged—they seemed to be interested in *everything*—while others were more motivated or achievement-oriented. Those traits could inspire learning even in the absence of overwhelming interest in a topic.) And yet, we've all seen counterexamples to this theory of stable interests: there's the indifferent student who hates science, encounters a brilliant chemistry teacher in high school, and goes on to get her Ph.D. in biochemical engineering. Or the student who sees English as a waste of time, only to come across a book that hooks her on literature for life.

Munroe recalls that he wasn't necessarily as attentive as he should have been in his own physics classes. "I remember at one point making a careful table of how many people each type of dinosaur had eaten in 'Jurassic Park'—both the book and the movie, of course, because the list of who dies has some major differences." And, although he'd liked science as a kid, he spent several years feeling unengaged by his school curriculum. "At some point, possibly after dissecting a squid, I started thinking that maybe I didn't like science after all," he said. He regained his enthusiasm only after a tenth-grade science teacher pointed him to a physics book when she couldn't answer a question he'd posed about radioactive decay. "I started flipping through it, and saw page after page about light, batteries, cranes, stars, waves, particles, electricity, and more," he recalled. "And I remember thinking, Oh, *this* is where the science I like is."

Recent research has explored how, exactly, interests evolve over our lifetimes. In a meta-analysis of sixty-six studies tracking interests over time (the average study followed subjects for seven years), psychologists from the University of Illinois at Urbana–Champaign found that our interests in adolescence had only a point-five correlation with our interests later in life. This means that if a subject filled out a questionnaire about her interests at the age of, say, thirteen, and again at the age of twenty-one, only half of her answers remained consistent on both. And while people's interests in college were more stable, correlating at just under point seven with their interests later in life, they, too, remained substantially malleable. What's more, the researchers found that interest in some fields, such as sports, was far more stable than interest in others, such as science.

What is it, then, that can capture our curiosity about subjects that once bored us? As it turns out, the approach Munroe tried out at M.I.T.—the absurd hypothetical—is exactly the kind of technique that we now know is likely to foster engagement. He has collected some of these hypotheticals in "What If?," an illustrated book of outlandish physics questions, out this month, that investigates serious scientific concepts. Could we really live, like the Little Prince, on an asteroid if it were big enough? Is it possible to build a jetpack using downward-firing machine guns? Even someone who has never given much thought to concepts like thrust-to-weight ratios may be suddenly drawn into a world where AK-47s ("a minimum of 25 but ideally at least 300") enable us to lift off into space.

* * *

In 1966, the University of Toronto psychologist Daniel Berlyne proposed that curiosity arises when we encounter uncertainty or ambiguity in our environment, whether it's physical (a place or an object we haven't seen before) or mental (a word we don't know, a question we can't answer). Any time our experiences don't quite correspond to what we've previously encountered—a phenomenon that the Carnegie Mellon psychologist George Loewenstein later called the "information gap"—we start to pay attention. But uncertainty and ambiguity alone aren't sufficient to generate sustained interest over time. You may not know whether the sun revolves around the Earth or what that orange thing on the sidewalk is, but you may not particularly care, either. What's needed beyond a gap in knowledge, Berlyne argued, is incongruity and surprise: something that seems to outright contradict what we already know, or to be otherwise extremely novel. When new ideas or experiences somehow don't mesh with old ones, we react with curiosity.

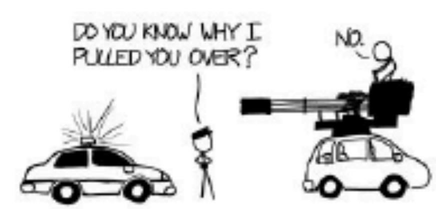
We develop this instinct from an early age. Babies will gaze longer at things they haven't seen before than at things they have. They also engage more with events that seem to contradict a physical law in their environments, such as a seemingly impossible motion—a ball that appears to go through a solid object, for example, instead of coming to rest against it. This is the very sort of absurd scenario that Munroe's book describes.

Berlyne's formulation has proved remarkably accurate, albeit not completely sufficient, to explain when and how curiosity can be piqued. Last year, Loewenstein and his colleague Russell Golman built a new model of information-seeking, designed to capture the circumstances that lead us to strive for new knowledge. To Berlyne's ideas of surprise and incongruity, Loewenstein and Golman added importance, salience, and epiphany. Our curiosity is strongest, they found, when we have the chance to resolve uncertainty about something that is personally relevant to us, that demands our attention, and that has the greatest potential to lead to broader insight.

That same year, a team led by the Columbia University neuroscientist Jacqueline Gottlieb lent further support to that structure by adding both neural and eye-movement data to the mix. Gottlieb and her colleagues concluded that when novelty, surprise, uncertainty, and randomness (the basic equivalent, in their formulation, of incongruity) come together in the presence of an information gap, our motivation systems jump into high gear and we begin to search more actively for new information.

Munroe's absurd "what if"s combine these elements to maximum effect. For one, the question format helps to inspire interest, because questions are by nature uncertain—they inherently create an information gap. And hypothetical questions, in particular, are designed to be novel and incongruous, creating juxtapositions that don't exist in the real world. Where a normal, expected, and unsurprising question lacks the power to draw us in —How much energy does it take to light a dozen light bulbs?—the absurd hypothetical makes us want to read further. The "what if"s also happen to be salient, both because they describe fundamental aspects of nature and our environment and because the cartoons capture the eye and the mind simultaneously. They even satisfy Loewenstein and Golman's requirement for epiphany: while reading a specific narrative scenario, you learn about broader physics concepts that can satisfy other information gaps.

Munroe's questions offer another form of catnip, too, one that I would include in any complete model of curiosity: they tell stories. The questions he chooses to answer are narratives. We're moving the population of the world to Rhode Island. We've contracted a strange disease that causes our DNA to mysteriously vanish. We're threatened by a freak rainstorm that will consist of a single drop rather than a steady stream of rain. The hypotheticals are memorable because they are truly hypotheticals: narrative scenarios that could unfold in some bizarre rendition of alternate reality.



Our minds love stories: when we experience something, we tend to spontaneously create a narrative that makes sense of it. And we're not only drawn to this way of relating to the world; we remember information conveyed in stories better than information presented any other way. Even the famed memory-palace technique—recalling items by assigning them to a space you've created in your mind—relies, in large part, on storytelling. The more engaging (and incongruous) the mnemonic we employ for an item, the easier it is for us to retrieve it.

* * *

It is true, of course, that many interests are stable. I've always loved reading, for example, and I still do. But the right combination of factors can stimulate our curiosity in just about anything, even topics we've traditionally shied away from. I've never taken a physics class—the very possibility made me want to throw away my course catalogue. And yet I read "what if?" in one sitting, not realizing how much physics I'd absorbed in the process. Even Munroe himself came around to the non-physical sciences he'd spurned earlier on. "I mean, squid *are* pretty cool," he told me. "Some of them can control the color of individual skin cells, so they're like little TV screens!" Give biology the right frame, and suddenly it's as fascinating as radioactive decay.

One reason I never wanted to learn physics is that I couldn't see how it related to my goal of being a writer. I'd never need it, I reasoned. My curiosity remained low. The absurd hypothetical circumvents that problem, by making any topic, no matter how remote, seem engaging. It's interesting in and of itself, whether or not it's likely to "apply" in the practical sense of the word. I don't particularly care that physics is practically useful for an engineer or an architect. But after musing on the Little Prince's dilemma, I'm far more aware of the intricacies of gravity and escape velocity than I ever thought possible.

It makes sense, given Munroe's intuition about curiosity, that the "what if?" he thinks about in his spare time has little to do with his chosen career in physics. "I'd love to build a time machine and hold a spelling and grammar contest between kids now and those same kids twenty years ago," he said. "Everyone's always complaining that text-speak and autocorrect are destroying writing ability, but I suspect the modern kids would win, hands down." He may be right, especially if kids today have been taught to spell in surprising, novel, incongruous, and relevant ways. What if a Xoloitzcuintli suddenly grew enough hair to stay warm in Alaska? Perhaps then you'd remember how to spell its name.

Images courtesy Randall Munroe / Houghton Mifflin Harcourt

The General Versus the Specific

> *In October 2006, nearly six thousand people worldwide perished in hurricane-induced floods.*

Quick, what do you feel after reading that sentence? My guess is, you feel a little confused by the question. Now imagine a wall of water coming straight toward a small boy, who clings desperately to his frantic mother. Trying to soothe him, she whispers, "Don't worry baby, I'm here, I won't let you go." She feels him relax in the moment of deafening calm just before the water rips him from her arms. The sound of his cry above the cacophony of destruction—trees ripped from the ground, houses smashed to splinters—will haunt her for the rest of her life. That, and his look of utter surprise as he was swept away. *I trusted you*, it seemed to say, *and you let me go*.

Now how do you feel? This time, the question is clear. Watching the flood claim that one little boy is far more gut-wrenching than hearing about six thousand anonymous people perishing in various floods, isn't it? I'm not suggesting your heart doesn't go out to all the flood victims and their families. But chances are, when you read that opening sentence, you didn't feel much of anything.

Don't worry. This isn't a psychological test to reveal your deep-seated pathological tendencies; rather, it highlights how we humans process information. As counterintuitive as it may seem, even the most massive, horrendous event, when presented in general, doesn't have much direct emotional impact, so it's easy to sail right by it almost as if it wasn't there. Why? Because we'd have to stop and *think* about it in order to "manually" do what a story would have done: make it specific enough to have an

emotional impact. And why would you do that? As Damasio says, "Smart brains are also extremely lazy. Anytime they can do less instead of more, they will, a minimalist philosophy they follow religiously."[6] Since your brain's probably much more interested in thinking about something that matters, like why your spouse is late again tonight, it's probably not going to work at envisioning—wait, what was that again? A terrible flood somewhere years ago? Especially because hey, there's nothing you can do about it, and besides, it would just make you feel bad, and god knows you have enough on your plate with your knucklehead spouse, who your mother warned you about, but did you listen? *Huh?* Flood? You talking to me?

The point is, if I ask you to think about something, you can decide not to. But if I make you feel something? Now I have your attention. Feeling is a reaction; our feelings let us know what matters to us, and our thoughts have no choice but to follow.[7] Facts that don't affect us—either directly or because we can't imagine how the facts affect someone else—don't matter to us. And that explains why one personalized story has infinitely more impact than an impersonal generalization, even though the scope of the generalization is a thousand times greater. In fact, it is only via a specific personalization that the point of a generalization is shot home. Otherwise, as Scarlett said, we can think about it tomorrow—which, given how much brain energy it takes to think about something that hasn't grabbed us emotionally, usually translates to a week from never.

Feel first. Think second. That's the magic of story. Story takes a general situation, idea, or premise and personifies it via the very specific. Story takes the horror of a huge, monstrous event—the Holocaust—and illustrates its effect through a single personal dilemma—*Sophie's Choice*. Thus the massive, unwieldy, unbearable vastness of its otherwise incomprehensible inhumanity is filtered through its effect on one person, a mother who must decide which of her two beloved children to spare. And because we are in Sophie's skin, we feel the ineffable magnitude of all of it: the Holocaust, the unspeakable cruelty, her ultimate decision. We are not just being *told* about its effect; we are experiencing it.

Indeed, feelings don't just matter—they are what mattering means.

—DANIEL GILBERT, *Stumbling on Happiness*

MOST OF US WERE BROUGHT UP to believe that reason and emotion are polar opposites—with reason as the stalwart white hat and emotion as the sulky black hat. And let's not even discuss which gender was said to wear which hat. Reason, it was thought, sees the world as it is, while that irrational scamp, emotion, tries to undermine it. Uh-huh.

Turns out, as neuroscience writer Jonah Lehrer says, "If it weren't for our emotions, reason wouldn't exist at all."[1] Take that, Plato! This is illustrated by a sad story that, even sadder, its real-life protagonist doesn't see as sad at all. Because he can't—literally. Elliot, a patient of Antonio Damasio, had lost a small section of his prefrontal cortices during surgery for a benign brain tumor. Before his illness, Elliot held a high-level corporate job and had a happy, thriving family. By the time he saw Damasio, Elliot was in the process of losing everything. He still tested in the 97th percentile in IQ, had a high-functioning memory, and had no trouble enumerating each and every possible solution to a problem. Trouble was, he couldn't make a decision—from what color pen to use to whether it was more important to do the work his boss expected or spend the day alphabetizing all the folders in his office.[2]

Why? Because, as Damasio discovered, the damage to his brain left him unable to experience emotion. As a result, he was utterly detached and approached life as if everything in it was neutral. But wait, shouldn't that be a good thing? Now that emotion couldn't butt in and cloud Elliot's judgment, he'd be free to make rational decisions, right? I think you know where this is going. Without emotion, each option carried the exact same weight—everything really was six of one, half a dozen of the other.

Turns out, as cognitive scientist Steven Pinker notes, "Emotions are mechanisms that set the brain's highest-level goals."[3] Along with, apparently, every other goal, down to what to have for breakfast. Without emotions, Elliot had no way to gauge what was important and what wasn't, what mattered and what didn't.

It is exactly the same when it comes to story. If the reader can't *feel* what matters and what doesn't, then nothing matters, including finishing the story. The question for writers, then, is where do these feelings come from? The answer's very simple: the protagonist.

When the events of the story are filtered through the protagonist's point of view—allowing us to watch as she makes sense of everything that happens to her—we are seeing it through her eyes. Thus it's not just that we *see* the things she sees—it's that we grasp what they *mean* to her. In other words, the reader must be aware of the protagonist's personal spin on everything that happens.

This is what gives narrative story its unique power. What sets prose apart from plays, movies, and life itself is that it provides direct access to the most alluring and otherwise inaccessible realm imaginable: someone else's mind.

What Rapidly Unraveling Situation Have You Plunked Me Into, Anyway?

Let's face it, we're all busy. Plus, most of us are plagued by that little voice in the back of our head constantly reminding us of what we really should be doing right now instead of whatever it is we're actually doing—especially when we take time out to do something as seemingly nonproductive as, um, read a novel. Which means that in order to distract us from the relentless demands of our immediate surroundings, a story has to grab our attention fast.[8] And, as neuroscience writer Jonah Lehrer says, nothing focuses the mind like surprise.[9] That means when we pick up a book, we're jonesing for the feeling that something out of the ordinary is happening. We crave the notion that we've come in at a crucial juncture in someone's life, and not a moment too soon. What intoxicates us is the hint that not only is trouble brewing, but it's longstanding and about to reach critical mass. This means that from the first sentence we need to catch sight of the breadcrumb trail that will lure us deeper into the thicket. I've heard it said that fiction (all stories, for that matter) can be summed up by a single sentence—All is not as it seems—which means that what we're hoping for in that opening sentence is the sense that something is about to change (and not necessarily for the better).

Simply put, we are looking for a reason to care. So for a story to grab us, not only must something be happening, but also there must be a consequence we can anticipate. As neuroscience reveals, what draws us into a story and keeps us there is the firing of our dopamine neurons, signaling that intriguing information is on its way.[10]

What Does *That* Mean?

As readers we eagerly probe each piece of information for significance, constantly wondering, "What is this meant to tell me?" It's said people can go forty days without food, three days without water, and about thirty-five seconds without finding meaning in something—truth is, thirty-five seconds is an eternity compared to the warp speed with which our subconscious brain rips through data. It's a biological imperative: we are always on the hunt for meaning—not in the metaphysical "What is the true nature of reality?" sense but in the far more primal, very specific sense of: *Joe left without his usual morning coffee; I wonder why? Betty is always on time; how come she's half an hour late? That annoying dog next door barks its head off every morning; why is it so quiet today?*

We are always looking for the *why* beneath what's happening on the surface. Not only because our survival might depend on it, but because it's exhilarating. It makes us feel something—namely, curiosity. Having our curiosity piqued is visceral. And it leads to something even more potent: the anticipation of knowledge we're now hungry for, a sensation caused by that pleasurable rush of dopamine. Because being curious is necessary for survival (*What's that rustling in the bushes?*), nature encourages it. And what better way to encourage curiosity than to make it feel good? This is why, once your curiosity is roused as a reader, you have an emotional, vested interest in finding out what happens next.

And bingo! You feel that delicious sense of urgency (hello dopamine!) that all good stories instantly ignite.

ADVICE FOR OUTREACH COMMUNICATORS

Your goal as an outreach writer is always the same: Have the reader understand, comprehend, and apply your information to affect their beliefs, attitudes, decision making, and actions. To meet that goal, you must write differently for different audiences.

People who work in the technical field you are describing already possess the banks of prior knowledge to create context, relevance, and empathy. They need only the new information. That is not true, however, for the wider audience you hope to reach with your outreach writing.

It may be technical information that you want to convey. But it is *story* that creates context and makes it relevant. It may be new science developments you want to communicate, but it is character that makes it meaningful. It may be important new concepts you want to communicate, but it is the details of the human experience that make it memorable. It may be new accomplishments you want to describe, but it is the struggles en route to those accomplishments that will make readers relate to, and care about, the accomplishments.

Bruner (1986) put it this way. ''Science strives to define universalities of the world that are context independent. Stories strive to create universalities through context dependent situations.'' The two are neither mutually exclusive nor incompatible. Instead, they act as complements to each other, creating a powerful and effective whole. Use story structure to create context and relevance for unfamiliar topics.

Put a face on it. Science doesn't happen by itself. The people who do the work, their challenges and struggles *are* the story. Tell readers about the people in order to make the science comprehensible and meaningful.

Avoid the family story syndrome. When telling family stories to family members, there is no need to include character description (everyone already knows them), goal, or motive. (These also are general common knowledge.) Family stories are then reduced to plot descriptions laden with family jargon and phraseology that have developed over the years. It's fine for those in the family, but meaningless and boring for those outside the family.

Science fields and scientists have traditionally written for other scientists already in the particular field of science. For brevity's sake, they have left out the same information omitted from family stories and have achieved the same result. Science writing is perfect for those already in that particular field, but a morass for others. The job of the outreach writer is to translate from ''family'' jargon and its implied information into the story-based form needed for non-family members.

INTERVIEW

THE SCIENCE OF STORY-TELLING

Tony Perez

A Conversation with Robert Krulwich and Jad Abumrad of Radiolab

A slow crescendo. Throat clearing. Bleeps and bloops. A series of voices spliced together. *You're listening to Radiolab (lab, lab lab . . .) from* WNYC.

Cut.

Jad Abumrad and Robert Krulwich sit on high stools in front of a couple thousand people in Seattle's 5th Avenue Theater. They've taken their show on the road, re-creating for huge, and not exclusively NPR-looking, audiences what they typically broadcast from the safety of their Manhattan studio. Abumrad—in an untucked button-down and sneakers—fiddles with his laptop, while Krulwich—blazered and blue-jeaned—looks down at his notes. To stage right, a cellist with extravagant tights and a postapocalyptic haircut plays a long, deep note.

Krulwich begins to describe Aristophanes's speech on the origins of love, his contribution to Plato's *The Symposium*. He explains that in primal times, we humans were born not as individuals but as couples, conjoined at the back. Eventually, as tends to happen in these types of stories, the gods felt threatened by their creation, so Zeus hurled bolts of lightning (cue sound effects, courtesy of Abumrad) from the heavens and split the creatures in two. We were thus alone, but left with the memory of—and a longing for—our other halves.

Over the course of the next hour, Abumrad and Krulwich talk brain scans, Jimmy Carter's hair part, a molecular reading of *Through the Looking Glass*, and antimatter . . . anything that might broaden their understanding of that particular episode's theme: symmetry.

Radiolab is more than a science show, or anyway, it's a science show for people who might not otherwise bother to tune in to such a thing. Krulwich, who previously hosted PBS's *NOVA*, and Abumrad are flâneurs of the sciences—wandering and wondering, favoring experience over explanation. They tell stories, talk to subjects, interview experts, and bicker among themselves, then piece it all together into the most densely produced hour on the radio—something akin to *This American Life* with DJ Shadow on the soundboard. One minute they'll dissect the minutiae of electrocardiographic monitoring; the next minute they'll break your heart.

Now in its tenth season, *Radiolab* has evolved from a Sunday-night AM-radio experiment to a nationally syndicated show broadcast by over three hundred stations. It has upward of two million listeners and a wildly successful podcast. In September of last year, the MacArthur Foundation saw fit to award Abumrad one of its "genius grants"—no small praise, or sum of money.

I spoke with Abumrad on the phone from his office at WNYC, and I sat with Krulwich over breakfast (well, yogurt and peach pie) at the Edison Hotel's coffee shop in midtown. The following is a composite, chopped and screwed in my best *Radiolab* impression, of those conversations.

TONY PEREZ: There are certain magazines that have stood for a particular aesthetic or way of thinking; I think of George Plimpton's *Paris Review* or Gordon Lish's run at *Esquire*. *Radiolab* seems to have a stable of writers—such as Jonah Lehrer, Oliver Sacks, E. O. Wilson—that represents a different way of talking about science. What is it that you think unites these people?

ROBERT KRULWICH: They're probably better described as teachers. That's the quality you need: to be able to explain science carefully, and slowly, and stupidly if you have to—or *cunningly*, I'd say. We invite people who can put into their voice, somehow, the surprise and beats of making a discovery. That tends to be a teacherly talent. A guy like Neil deGrasse Tyson is extraordinarily good at acting as though he's thinking this for the very first time. There's something of a little boy in Tyson—and in Oliver Sacks, and in Ed Wilson—who comes out and plays. There's a bit of a campfire quality to the whole thing.

JAD ABUMRAD: I think there's a certain attitude at the core of every story we tell, sort of a sense that you're wandering through this world and have to stand back in awe of it. It's a very different attitude. A normal journalist or broadcaster will go to report on a story, figure it out, then report in a very podium-style way what he knows. All the ups and the downs, and the figuring it out, and thinking you know, and realizing you don't know—all of that happens off frame.

But here, it's very important to show how we're moving through the information. You're encountering things that you don't know, and jumping to conclusions that turn out to be wrong. But in the end,

> We invite people who can put into their voice, somehow, the surprise and beats of making a discovery. That tends to be a teacherly talent.

you go through this very rigorous step-by-step walk until you get to the edge, and you can sort of stand and look at the world in a state of simple wonder. I think that's what it is: the sense that if you actually move through things, you'll get to places that shake your perspective.

RK: One of the tropes of journalism—particularly high journalism—is you go off and learn everything, then you artfully report it back. But it's already done, it's cooked, by the time you serve the meal—as would be the case in most restaurants. In ours, we cook it right in front of you. Presumably, that should bring you in. But it *does* bother some people.

JA: Then there are the form elements—narrative storytelling, wrapping technical details in human experience. All of that binds Robert and me together with our writers. We all share that sense of how to do it. But at the core, it's something to do with curiosity and wonder.

TP: Wonder, even more than science—especially as the seasons have gone on—seems to be at the heart of the show. I came up on the liberal-arts side, the English department, where the best texts aren't about hard answers but about opening up bigger, more complex questions. That isn't how we're typically trained to think about science. *Radiolab* seems far more interested in asking than answering.

RK: That's true. The answers, in some ways, are temporary in science. It's not like religion.

JA: To be completely honest with you, I couldn't care less about science as a geography. My parents are scientists; it's not as if I have any antagonism toward it. But I do have an antagonism toward the institution of science journalism, which seems very much about covering what happens in laboratories—these things that get put out by universities in press releases. That kind of stuff doesn't interest me at all.

In your question, you sort of put your finger on it. It's sort of about mystery, but it's not pure mystery—if that were the case, you might as well just sit in your dorm room and smoke pot. It's a wrestling match between *that* impulse and what the scientists are doing. There's a rigor and a specificity and an empirical approach that scientists have, which I could never do without.

> You want to have this gunshot of amazement at the top of every story. Then you proceed to *de*mystify it.

At the same time, there's that sense of just being completely amazed. The show is the tug and tension between those two things.

TP: And how does that tension develop?

JA: In every piece, we start by mystifying something. You want to have this gunshot of amazement at the top of every story. Then you proceed to *de*mystify it. Then you *re*mystify it at the end in a new way. If I could distill every story I tell to those three moves, I'd be happy. You begin with sort of simple, cheap wonder, you go to science—to someone who can analyze the underlying assumptions—then you put it back together in a new way, but where you can still stand in amazement. But it's not cheap anymore; it's tested.

The two impulses pull on each other. Part of my brain is that guy in the dorm room smoking pot and just going, "Wow, is that me in the mirror?" And part of my brain wants to be an adult and understand how the world *really* works. I don't want to kill that first guy, but there should be a kind of armed truce. That's how it works for *Radiolab*. If it's one or the other, I get very uncomfortable. If we do too much hard science without any sense of poetry or mystery, I want to jump out the window. But if everything is silly and soft, and you don't have that sense of rigor, I feel like I'm letting myself and our listeners down. It's somewhere in the middle; it has to be a balance.

TP: I'm interested in that balance of the hard science and the emotional core. Vivian Gornick wrote a great book on writing called *The Situation and the Story*. An insultingly oversimplified explanation is that the "situation" is the series of events that comprises the plot, and the "story" is what's happening below the surface. My favorite thing about *Radiolab* is the way you balance the two. I'm always as interested in the hard science of the situation as I am the emotional core of the story: the exploration of neuroscience *and* the story of a woman in a coma. How do you build segments with both of these elements in mind?

JA: I think it comes from both directions equally, really. The stories are the harder thing to find. It's an easier place to start, for me, when you have a great story that seems pregnant with something. Then I can invite a smarty to talk about neuroscience or whatever. That's easier for me to conceptualize, but that's not always how we start. I know Robert often works the other way. He'll have a broad concept or a new bit of research that will lead him to go look for the story. The show really evolved in that juxtaposition. You have those two things happening side by side; you have some kind of human experience but you also have a way to examine and understand it.

In my opinion, experience can never be taken out of the equation. It doesn't always have to be a story in that classic "Once upon a time" sense, but even when you're explaining some arcane concept—like the dopamine reward system, which we've talked about fifteen times—even then it has to feel physical; it has to feel like an experience. If it ever feels like a lecture, if it ever feels didactic, we've lost. That's where the sound comes in; that's where the writing comes in; that's where the pictures and visuals come in. It has to feel like a movie. It can never feel like something that's just being explained.

RK: There's a bottom-up approach and a top-down approach. I tend to be more comfortable with broad architectures. In the case of "You Are Here" [season 9, episode 2], someone suggested doing a show about mapping. So I read a book about the map on which the word *America* first appeared. Then we met a mapmaker—a very interesting fellow—and that led to a discussion of place. Jonah [Lehrer] said he could help us explain place neurons [*Ed. note: place neurons are cells in the hippocampus that help create a cognitive map of an animal's environment*], and that seemed kind of interesting.

Meanwhile, Jad was beginning to wonder about people in the South Pacific who go from one *teeny* island across a vast stretch of emptiness to another teeny island without the use of sophisticated navigational tools. How do they know where they are going? Well, one of them claimed it was his testicles. "My testicles guide me," he said, and of course his wife said, "That's ridiculous ... I don't have testicles and I can do it." We got very interested in that and did a whole series of testicle-related conversations with South Pacific Islanders. The mapping thing began to fall out, but the stuff from Jonah was developing really well. We then found someone who had a problem with her mapping sense. Things kept shuffling.

Finally, a friend called and said, "I have this neighbor who had a terrible thing happen to her. Her boyfriend's a friend of mine; I think he's a great hero, and you should help them somehow." I went to meet Alan, the boyfriend. His girlfriend was swimming in a coma, and he was fighting to pull her back out. I thought that, in his way, he was acting like Jonah's place neurons. And it was just this amazing story. So all of this was going on simultaneously, and the show was in a continuous shuffle. In the end, the maps, where it all started, shuffled out and a sense of place shuffled in.

TP: I'm always impressed by the jumps you make without it feeling like a stretch, those transitions between a profound story and the more complicated material.

JA: Those transitions are the things we'll do thirty takes of over the course of a production cycle, just to make sure we get them right. We're always trying to figure out the most plainspoken but genuine way of making a connection. It's really hard sometimes, figuring out what the apple has to say to the orange.

TP: Robert, you mentioned that your approach bothers some people. *New York* magazine described you as someone who could simplify science without making it simple, but do hard science people feel differently?

RK: Yes, it *is* abrasive to people. Throughout my career, there's always been a continuous ten percent—the "Fuck you" ten percent—that says, "Why can't you use fancy words?" "Why can't you talk like an adult?" "Why can't you sound like a person who knows what he's talking about and articulates it from a place of knowledge and power?" This is a choice that we make. *Radiolab* chooses to put two people, who, admittedly, don't know a lot at the beginning, on a path where they quarrel and wonder and poke and ask and whisper to each other—that stuff is done on purpose.

TP: Where does that resistance come from? Is it academia?

RK: Yeah, mostly. I would say pedants of one kind or another, but they would probably feel differently. It's interesting; on my blog, I'm very clear that the voice there is a chatty voice, not a newswriting voice, but still, it upsets people every day. I say, "You know, this is *not* a news story. We're not in a news setting. This is an essay. You can wander around here and muse. It doesn't have the discipline of an athletically gathered, extremely accurate, honed piece of journalism." People don't always know that.

TP: But part of *Radiolab*'s popularity has to be due to its success in making hard science accessible to nonscience people (like me). I love how you take turns playing the straight man—almost like Carson or Letterman deferring to a guest comedian, acting as a stand-in for the audience, some kind of layperson by proxy.

JA: Most of the time, it's genuine that one of us does know more than the other about a particular topic we're covering. Oftentimes, I'll intentionally keep Robert in the dark. It's often the case that we'll just start rolling tape and I'll explain a concept to him.

TP: I imagine that helps keep the banter fresh.

JA: Yes, sure. And there are times, to be honest, when it's more constructed, when there's a bit of acting involved, when one of us is playing a role . . . but it's a role that's based on a previous version of ourselves. There have been times when Robert knew something that I didn't know, and we actually have had that conversation off tape. We'll carry that into the studio and we'll reconstruct those moments as best we can. We'll improvise, sometimes, fifteen takes trying to get a moment that feels real to us, to who we were before we got into the studio.

People may not like science-y stuff, may not like mathematics, but what everybody likes is a friendship. Something warm that glows a little.

So, yes, the straight man is a construct, sort of a vaudeville trope. But it *is* based on the inequalities that exist within any friendship. At any time, one of us knows more than the other. And we're always trying to get the other guy to see the world as we're seeing it. That's genuine. Where, I think, we depart from the vaudeville trope is that I *really* want Robert to join me in being excited about something, or he wants me, or our guests, to join him. We all want, at the end of the day, to stand together and give each other a big hug. We depart from the shtick, I hope, at the end of each piece.

RK: Even though in the beginning neither of us knows anything, one will become the one who knows, and one will be the one who doesn't know. We'll say, "You take this one," or "I'll take this one." But oftentimes we're guided by actual differences in opinions. We deeply disagree on certain things. It's a source of great happiness to us when one can say, "You *really* think . . ." And we don't try to fake that; it wouldn't work. But we have some very different views.

TP: But the affection you have for each other seems key.

RK: Of course. People may not like science-y stuff, may not like mathematics, but what everybody likes is a friendship. Something warm that glows a little. If something fun and interesting is going on over there and if you're invited, there's a pull. I said to Jad at one point, "The fact that we feel this way about each other is a huge advantage to us, if we're not embarrassed by it. We should act like we feel." The whisper of affection and curiosity and play—mostly play—will get a lot of people into the tent. We could be talking about food, or flowers, or sports, but if we talk about it in this way, we will attract people. That's the way people are.

TP: At the same time, those little arguments and tensions certainly keep the show moving along. Are there particular differing beliefs or opinions that you keep coming back to?

JA: Absolutely. There are instances when we disagree, and there are real disagreements—friendly, but real. Anything to do with God, and that comes up relatively frequently. These are big questions we're examining, religious-sized questions. It's easy to talk about God when you're talking about the birth of the universe. There are

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questions that get you to that place very quickly. And we do disagree about the nature of things. The question, are humans special? is one of those overarching thoughts that continually barges its way in. Robert and I disagree about that. He tends to take the point of view that we are, and I take the view that we aren't.

TP: Robert, do you see this battle between science and religion as something of a false binary?

RK: Well, if you're asking, "What happens after death?," "What is the conclusion of everything?," or "Where do we all come from?," there are now scientists who propose answers. They didn't used to, but they do now. So there are two different stories and they are, I suppose, rivals. I don't think you can simultaneously believe in heaven *and* a death of all sentience, that is, when your nerves and muscles decay, that's the end of you. Those are conflicts.

But on the other side, if you're asking ethical questions or *why* questions, then I think they can coexist. Why do nice people have terrible things happen to them? Well, because there is a randomness to the world, and accidents always happen, and there is no message in it, no lesson in it . . . *or*, there is, and there is some author outside of things who is discriminating. I don't think science can say yes or no to that, or even try. In that area, the area of *why*, I think there is a place where you can be of two minds. I don't know why, but I'm quite comfortable being of two minds.

TP: How do listeners respond to that sort of thing?

RK: *Radiolab* has a very broad audience, and among the people who listen are lapsed Christians. Former students at Bible schools, preachers, people who have come from various evangelical traditions in which questioning is not really welcome. Some of these people listen and notice that we keep asking questions and that we're comfortable as questioners, which is the most viral thing we've got. We're getting people to examine fundamental questions gently, but the real accomplishment is we give people a little more power to wander in a territory where they might not ordinarily. That feels like a great thing.

TP: Considering that the same people pushing creationism are the ones stripping public radio of federal funding, is it difficult to navigate a world where every idea in the marketplace, regardless of its validity, is expected to be treated with equal weight?

JA: Honestly, no. I would have expected to, but we've never bumped up against that. We're lucky in that we work in a place full of people who are deeply committed to our content and editorial mission. No one here would ever try to impose a false sense of balance; they would never tell us what to say or think. When Robert and I get into arguments that touch on a tension between science and religion, it's perfectly genuine; it's for no reason other than what we're feeling and thinking in the moment. People will yell at us in our comments field online, but that's about it. We've never gotten any pressure from one group or another. I always assumed that it's because we fly a little below the radar. I don't know if that's the case anymore, but I just assume that the people who like the show like those arguments. They don't run away from them; they enjoy them.

RK: No, not really. I don't know why. Maybe because we haven't ventured yet into stem cells; we've done "Where does life end?," but we haven't done "Where does life begin?" So far, for some reason—it isn't any calculated reason—we haven't walked right into that territory. Part of it is that we do only ten shows a year. We can't afford to do something that's so topical that it goes stale. We need shelf life, so part of our logic has been to avoid things that are "right now."

But maybe we haven't felt the pressure because we haven't gotten into the middle of the debate. We are talking with *This American Life* about doing a joint program about global warming, so maybe that will do it.

TP: Well, I'm glad to hear Michele Bachmann isn't coming after you.

JA: Not yet.

TP: Does the current political climate worry you? Do you think public radio is in danger?

RK: No, I think it's unbelievably healthy. The programs that most of us have heard of are ninety-eight percent paid for, then the government puts a couple of pennies on the table. What's at risk are those stations in eastern Montana or Alaska that don't get a lot of listener support but do get a lot of listeners. If you live in a remote area, it's a way to hear something that isn't the CBC or the BBC. That is at risk.

I live in New York City. WNYC was owned by the city of New York, and about fifteen years ago, the listeners got together and said, "You're having a budget crisis. Can we buy it from you?" The then-mayor, Ed Koch, came up with a price and the listeners bought it. It didn't hurt. That station has produced one show after another. It's entrepreneurial and it creates a culture of yes as opposed to a culture of no.

The NPR culture, at this point, is all about "What can we do to not tick off the congressman from Knoxville?" That's no way to run a network.

TP: How does what you're doing fit into the public radio paradigm?

RK: We are thinking about public radio *a lot*. What happened in public *television* is that a group of people, very roughly of my generation, came in during the 1970s and said, "This is wonderful! We'll make magazines; we'll do *Washington Week*; we'll create *Sesame Street*; we'll do British-theater things that you can't get here."

But the usual process is that somebody gets fired and someone replaces him. Lou Rukeyser walked into *Wall Street Week* in 1972, and in 2002 he was still doing exactly the same thing, endlessly and over and over again. The people who came after couldn't get jobs because these people never left. There is something not unlike rigor mortis that has set into public television. I *think* it's dead.

So about fifteen years ago, a bunch of folks in public radio, led by Ira Glass and a guy named Jay Allison, said, "Uh-oh, this sound has become so predictable that you know you're listening to public radio as soon as you graze the dial across those 90s and 80s stations." Ira and some friends created the Third Coast International Audio Festival for the express purpose of trying to seduce kids who were then Jad's age. That's where Jad first encountered a lot of these radio people. Jay created PRX, which basically enables you to put your own thing on the radio; it's essentially an ongoing job fair, and it's moderately successful. *Radiolab* was part of that, and I thought, "Here's this young guy who has a set of beats in him that I've never heard before."

TP: Jad, you really developed the sonic aesthetic of the show. Can you talk about how that evolved or why you thought it would be a good format or style?

JA: I guess I could make up some bullshit about what I think I was doing, but I don't really know. The show began when it was just me on Sunday night from 8:00 to 11:00 on the AM frequency here in New York. I didn't know it at the time, though I had an intuition, but no one was listening. Really, no one, like, probably *zero* listeners. I was just making it up and trying to create a sound that made sense to me. Not having grown up around radio, I had no idea what broadcasting *should* sound like. I was listening to *This American Life*, so I had that sound in my ears. I was trained as a composer and had been listening to a lot of really complicated, layered, avant-garde music. I knew that stuff could be alternately annoying or absorbing, so I wanted to work that. Not in a way that felt experimental, just in a way that made sense to me.

The mood that I thought about in the beginning was the sense of a dream. When you listen to someone tell you about a dream, it's almost like you're in a dream together. That's encouraging to me, that there's a kind a trance people enter into when they hear a story. I wanted to create a sound that somehow induced that trance. But at the same time, there's something very exciting about breaking it up with strange blurts and spastic noises. There is always a tension between a kind of dreamy wash and a more percussive alienating sound. I was trying to work those in, but it was on a purely intuitive level.

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TP: Robert, what did you initially think of Jad's style?

RK: I thought it was very important that his sound get on, and get heard, and get joined, and get elaborated upon. One of your jobs or duties at a certain point—if you're an impresario (which you always have to be, in a way)—is to take what you know and stare at what you don't know. When you hear something that strikes you as at least vaguely beautiful—a lot of times what Jad does is vaguely ugly to me; I don't understand it, but I can hear my *kids* liking it and listening to it as ordinary fare, as if it understood their beats—you have to think, *If that brings in an audience, let's do that.* There are a lot of parts of *Radiolab* that I don't understand, but I *know* it has this reach.

So I just say okay. Jad has final cut on every show. It has to end with someone, and it can't end with me. I'm going to die at some point—I mean, I hope I die earlier than he does—so it should be his. That's part of the transfusion that is required in any of this.

NPR was the one thing my generation made that wasn't there before. We got CBS, we got NBC . . . we made PBS, but we fucked it up. NPR turned out to be a gift, but only if it becomes the next generation's property. If it's just their parents' radio, then it will die. *Radiolab* is a way of dealing with that.

TP: How much time do you spend on a given episode? Are you still doing ten a year?

JA: Yeah, plus a bunch of shorts—I don't remember exactly how many, probably about fifteen. We do one episode every six weeks, and that's pretty much the full arc. We'll have a show that's incubating in the background for a while, where you know you have one thing and you're looking for another or you need more research, but once we finally hit go, it's six weeks start to finish. Some shows come together really fast, and others just don't want to be born . . . you have to drag them out kicking and screaming.

RK: But the process by which we do all of this is insane. We'll take up a subject, we'll go out and interview people—often together, but sometimes apart—somebody does a cut, then we take the cut into the room and start talking; we'll say this doesn't work, or that doesn't quite make sense, or we need to get someone else. Then we do it

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again. We switch roles or we throw things out. Gradually, it starts coming together. Everything goes through nine or ten passes before it gets close, then we start with the music. Once it's scored, we ask, "Should we change our voices to react to the music around us?" What you get at the end is the sum of fifteen or twenty performances. It turns into a very fluid thing, but it's entirely artificial . . . except that it isn't. And it's insane. I've never done anything like this before; it makes no sense. The reason we can do only ten shows is that it's just that stupid . . . and it's as close as we can get to making something that's perfect.

JA: The sound stuff doesn't really enter in until about the fifth draft. That's when I kind of close the door, and when the show starts to sound like the show. Everything will be in place, but the musicality below the surface isn't there yet. It never really sounds like *Radiolab* until about that fifth draft.

TP: When do you know that it's done, that it's perfect?

RK: That's Jad. I'll make suggestions, but he doesn't have to take them. It's up to him at the end of the day where our final beauty rests. Though, it's interesting to me, either because he's seduced me or because we were doppelgängers from the beginning, we often agree. It's one of the crucial things, whether you're making a movie or a radio show—and maybe it's true about writing—to know when you're done. It's sort of like flower arranging. You have elements. You put them into a bowl. There are incomprehensively large numbers of combinations that could be made, but at a certain point, you feel somehow satisfied. It's a mysterious feeling. And if you feel satisfied together, it's a doubly mysterious feeling.

TP: More and more of my "radio" consumption is coming through podcasts. When I turn on the radio, I hear *Car Talk*, or *A Prairie Home Companion*, or a painful local call-in show. With podcasting, I listen, at my convenience, to the shows I like—*Radiolab, Bookworm, The Best Show on WFMU*. Considering the growing access to technology, is this the direction radio is going?

JA: I definitely see that as the direction we're going, and the kind of show we're interested in making. We see the podcast audience growing rapidly, and I'm glad about that. The kind of stuff we're making just lands better on an iPod than it does out of a box. People can experience it more intimately, because we're in their ear canals. It's much, much easier to comprehend all the stuff that's happening on the show if you've *chosen* to put it in your ear than if it's just randomly coming out of your car stereo. For us, podcasting has been a blessing.

RK: We create a very jewel-like production; it's very layered. When you stick two things in your head, you are a prisoner of what's coming in, and you can't help yourself. You become a coauthor. Radio is much more intimate than TV, but even the seven feet you're away from a radio is a big seven feet, from the storyteller's point of view. Once we're inside you, there's nothing else; it's like sex. You're in. You can have a conversation that's almost sexy in its intimacy, and its colors, and its subtleties. You can't have that just shaking someone's hand. When you fuck 'em, you can do all kinds of interesting things. That's the big difference. We didn't expect it, but it's made all of the difference to us. We went from seven thousand subscribers to fifty thousand, then Ira put us on his show and we jumped to a quarter million in an instant. We keep growing and growing, and I think it's because we are podcast friendly.

TP: Will that format change the way people are producing content?

JA: I don't know if it's the direction all radio will go, but I do know that kids below a certain age just don't own radios anymore. That's kind of an interesting situation. I don't know what that will mean for radio as a whole, if it will just migrate onto smartphones and things like that.

I do think that there's a serendipity that happens when you turn on old-school radio; you hear things you weren't expecting to hear, and that's kind of beautiful. A lot of the people who like the show began with those little collisions that happen when you're in your car and some story comes on. So there's a part of me that's sad that maybe that is happening less. I don't know if this has been your experience, but I subscribe to a lot of podcasts and listen to maybe one percent of them. There just aren't enough hours in the day. I wonder if that happens often, if people are actually listening to as many podcasts as they have.

But I will say, if you just stroll through the top twenty on iTunes or something, there are a lot of different sounds. I've been listening to Marc Maron's podcast a lot recently.

TP: I love his show.

JA: Yeah, he's really interesting, aside from those fourteen-minute commercials. He's this great, kind of unhygienic character. Whereas sometimes public radio personalities are very anesthetized and squeaky clean, he's not, and it's incredibly compelling. To me, it's great that there are these cool things sprouting up in meadows just adjacent to us. I like that, and I think they benefit us.

TP: What episodes or segments typify, for you, what *Radiolab* should be, both in terms of form and content?

JA: You mentioned the story of the woman in the coma. On a pure storytelling level, I feel like that is everything I want from the radio. There isn't a ton of science or philosophy inside that story, but if you ask me why I actually turn on the radio, it's so I might hear a story like that. And that's a case where we just got lucky.

But in terms of *Radiolab*, and the sound and synthesis we're aiming for, I think of the "Words" show [season 8, episode 2] and the different moves we make. We start with a woman who describes meeting a fellow who had no language until he was twenty-seven. It's just a pure story. Then we go to a really complicated psychology experiment involving rats and people in a white room—it was a terribly difficult experiment to explain, we must have done fifty different versions of it and it wasn't working in terms of the mood, or the scoring, or the explanation, until it suddenly did. But I remember reading about the experiment and saying to myself, "This is incredible. This gives me a completely new way of thinking about the power of words."

I can remember that feeling, but everything that happened after that was difficult and frustrating. It was all an attempt to reconstruct, for the listener, that feeling. We eventually got to a place with that story where I was really proud of it. It achieved a certain kind of dreamy poetry that's perspective-shaking in a way that I felt when I first discovered that idea. So I liked the balance in that first segment between a very narrative thing and something extremely cerebral and abstract. Overall, I think that show really captured the full palette of our moods in a way that sometimes shows don't.

RK: "Words," I think, was very special. I don't know how well you know that episode, but there's a guy who can't hear, and he discovers that things have names. The surprise of that not only shocks him, it also delights him. It allows him to find a place in the world. I just thought that was one of the more beautiful stories we've produced.

For some reason, I like the show about stress, with Robert Sapolsky. There's something about Sapolsky. If there's an E. B. White for your ear, it might be this strange neuroscientist from Stanford University. I don't know why it is, but he's just the most compelling storyteller. He talks about his father dying, then putting on his dad's shirt and putting his dad's pencils in the shirt pocket and mourning his father by becoming him. He'd lecture his class at school by telling them that even though the exam was coming up, and they all wanted to know what was on the exam, it was more important that they call their parents. He realized that he'd just *become* his father for a season. I found that completely bewitching.

It's always the occasions when the idea that's being examined and the heart that's being examined, which carries the idea, become so entangled that you can't stop thinking and you can't stop feeling. That's when you hit it.

IS THE SCIENTIFIC PAPER A FRAUD?

By Peter Medawar

I have chosen for my title a question: Is the scientific paper a fraud? I ought to explain that a scientific 'paper' is a printed communication to a learned journal, and scientists make their work known almost wholly through papers and not through books, so papers are very important in scientific communication. As to what I mean by asking 'is the scientific paper a fraud?' -- I do not of course mean 'does the scientific paper misrepresent facts', and I do not mean that the interpretations you find in a scientific paper are wrong or deliberately mistaken. I mean the scientific paper may be a fraud because it misrepresents the processes of thought that accompanied or gave rise to the work that is described in the paper. That is the question, and I will say right away that my answer to it is 'yes'. The scientific paper in its orthodox form does embody a totally mistaken conception, even a travesty, of the nature of scientific thought.

Just consider for a moment the traditional form of a scientific paper (incidentally, it is a form which editors themselves often insist upon). The structure of a scientific paper in the biological sciences is something like this. First, there is a section called the 'introduction' in which you merely describe the general field in which your scientific talents are going to be exercised, followed by a section called 'previous work' in which you concede, more or less graciously, that others have dimly groped towards the fundamental truths that you are now about to expound. Then a section on 'methods' -- that is OK. Then comes the section called 'results'. The section called 'results' consists of a stream of factual information in which it is considered extremely bad form to discuss the significance of the results you are getting. You have to pretend that your mind is, so to speak, a virgin receptacle, an empty vessel, for information which floods into it from the external world for no reason which you yourself have revealed. You reserve all appraisal of the scientific evidence until the 'discussion' section, and in the discussion you adopt the ludicrous pretence of asking yourself if the information you have collected actually means anything; of asking yourself if any general truths are going to emerge from the contemplation of all the evidence you brandished in the section called 'results'.

Of course, what I am saying is rather an exaggeration, but there is more than a mere element of truth in it. The conception underlying this style of scientific writing is that scientific discovery is an inductive process. What induction implies in its cruder form is roughly speaking this: scientific discovery, or the formulation of scientific theory, starts with the unvarnished and unembroidered evidence of the senses. It starts with simple observation -- simple, unbiased, unprejudiced, naíve, or innocent observation -- and out of this sensory evidence, embodied in the form of simple propositions or declarations of fact, generalizations will grow up and take shape, almost as if some process of crystallization or condensation were taking place. Out of a disorderly array of facts, an orderly theory, an orderly general statement, will somehow emerge. This conception of scientific discovery in which the initiative comes from the unembroidered evidence of the senses was mainly the work of a great and wise, but in this context, I think, very mistaken man -- John Stuart Mill.

John Stuart Mill saw, as of course a great many others had seen before him, including Bacon, that deduction in itself is quite powerless as a method of scientific discovery -- and for this simple reason: that the process of deduction as such only uncovers, brings out into the open, makes explicit, information that is already present in the axioms or premises from which the process of deduction started. The process of deduction reveals nothing to us except what the infirmity of our own minds has so far concealed from us. It was Mill's belief that induction was the method of science -- 'that great mental operation', he called it, 'the operation”

“of discovering and proving general propositions'. And round this conception there grew up an inductive logic, of which the business was 'to provide rules to which, if inductive arguments conform, those arguments are conclusive'. Now John Stuart Mill's deeper motive in working out what he conceived to be the essential method of science was to apply that method to the solution of sociological problems: he wanted to apply to sociology the methods which the practice of science had shown to be immensely powerful and exact.

It is ironical that the application to sociology of the inductive method, more or less in the form in which Mill himself conceived it, should have been an almost entirely fruitless one. The simplest application of the Millsian process of induction to sociology came in a rather strange movement called Mass Observation. The belief underlying Mass Observation was apparently this: that if one could only record and set down the actual raw facts about what people do and what people say in pubs, in trains, when they make love to each other, when they are playing games, and so on, then somehow, from this wealth of information, a great generalization would inevitably emerge. Well, in point of fact, nothing important emerged from this approach, unless somebody has been holding out on me. I believe the pioneers of Mass Observation were ornithologists. Certainly they were man-watching -- were applying to sociology the very methods which had done so much to bring ornithology into disrepute.

The theory underlying the inductive method cannot be sustained. Let me give three good reasons why not. In the first place, the starting point of induction, naíve observation, innocent observation, is a mere philosophic fiction. There is no such thing as unprejudiced observation. Every act of observation we make is biased. What we see or otherwise sense is a function of what we have seen or sensed in the past.

The second point is this. Scientific discovery or the formulation of the scientific idea on the one hand, and demonstration or proof on the other hand, are two entirely different notions, and Mill confused them. Mill said that induction was the 'operation of discovering and proving general propositions', as if one act of “mind would do for both. Now discovery and proof could depend on the same act of mind, and in deduction they do. When we indulge in the process of deduction -- as in deducing a theorem from Euclidian axioms or postulates -- the theorem contains the discovery (or, more exactly, the uncovery of something which was there in the axioms and postulates, though it was not actually evident) and the process of deduction itself, if it has been carried out correctly, is also the proof that the 'discovery' is valid, is logically correct. So in the process of deduction, discovery and proof can depend on the same process. But in scientific activity they are not the same thing -- they are, in fact, totally separate acts of mind.

But the most fundamental objection is this. It simply is not logically possible to arrive with certainty at any generalization containing more information that the sum of the particular statements upon which that generalization was founded, out of which it was woven. How could a mere act of mind lead to the discovery of new information? It would violate a law as fundamental as the law of conservation of matter: it would violate the law of conservation of information.

In view of all these objections, it is hardly surprising that Bertrand Russell in a famous footnote that occurs in his Principles of Mathematics of 1903 should have said that, so far as he could see, induction was a mere method of making plausible guesses. And our greatest modern authority on the nature of scientific method, Professor Karl Popper, has no use for induction at all: he regards the inductive process of thought as a myth. 'There is no need even to mention induction,' he says in his great treatise on The Logic of Scientific Discovery -- though of course he does.

Now let me go back to the scientific papers. What is wrong with the traditional form of scientific paper is simply this: that all scientific work of an experimental or exploratory character starts with some expectation about the outcome of the enquiry. This expectation one starts with, this hypothesis one formulates, provides the initiative and incentive for the enquiry and governs its actual form. It is in the light of this expectation that some observations are held relevant and others not; that some methods are chosen, others discarded; that some experiments are done rather than others. It is only in the light of this prior expectation that the activities the scientist reports in his scientific papers really have any meaning at all.

Hypotheses arise by guesswork. That is to put it in its crudest form. I should say rather that they arise by inspiration; but in any event they arise by processes that form part of the subject-matter of psychology and certainly not of logic, for there is no logically rigorous method for devising hypotheses. It is a vulgar error, often committed, to speak of 'deducing' hypotheses. Indeed one does not deduce hypotheses: hypotheses are what one deduces things from. So the actual formulation of a hypothesis is -- let us say a guess; is inspirational in character. But hypotheses can be tested rigorously -- they are tested by experiment, using the word 'experiment' in a rather general sense to mean an act performed to test a hypothesis, that is, to test the deductive consequences of a hypothesis.

“If one formulates a hypothesis, one can deduce from it certain consequences which are predictions or declarations about what will, or will not, be the case. If these predictions and declarations are mistaken, then the hypothesis must be discarded, or at least modified. If, on the other hand, the predictions turn out correct, then the hypothesis has stood up to trial, and remains on probation as before. This formulation illustrates very well, I think, the distinction between on the one hand the discovery or formulation of a scientific idea or generalization, which is to a greater or lesser degree an imaginative or inspirational act, and on the other hand the proof, or rather the testing of a hypothesis, which is indeed a strictly logical and rigorous process, based upon deductive arguments.

“This alternative interpretation of the nature of the scientific process, of the nature of scientific method, is sometimes called the hypothetico-deductive interpretation and this is the view which Professor Karl Popper in The Logic of Scientific Discovery has persuaded us is the correct one. To give credit where credit is surely due, it is proper to say that the first professional scientist to express a fully reasoned opinion upon the way scientists actually think when they come upon their scientific discoveries – namely William Whewell, a geologist, and incidentally the Master of Trinity College, Cambridge -- was also the first person to formulate this hypothetico-deductive interpretation of scientific activity. Whewell, like his contemporary Mill, wrote at great length -unnecessarily great length, one is nowadays inclined to think -and I cannot recapitulate his argument, but one or two quotations will make the gist of his thought clear. He said: 'An art of discovery is not possible. We can give no rules for the pursuit of truth which should be universally and peremptorily applicable.' And of hypotheses, he said, with great daring -- why it was daring I will explain in just a second -- 'a facility in devising hypotheses, so far from being a fault in the intellectual character of a discoverer, is a faculty indispensable to his task'. I said this was daring because the word 'hypothesis' and the conception it stood for was still in Whewell's day a rather discreditable one. Hypotheses had a flavour about them of what was wanton and irresponsible. The great Newton, you remember, had frowned upon hypotheses. 'Hypotheses non fingo', he said, and there is another version in which he says 'hypotheses non sequor' -- I do not pursue hypotheses

So to go back once again to the scientific paper: the scientific paper is a fraud in the sense that it does give a totally misleading narrative of the processes of thought that go into the making of scientific discoveries. The inductive format of the scientific paper should be discarded. The discussion which in the traditional scientific paper goes last should surely come at the beginning. The scientific facts and scientific acts should follow the discussion, and scientists should not be ashamed to admit, as many of them apparently are ashamed to admit, that hypotheses appear in their minds along uncharted byways of thought; that they are imaginative and inspirational in character; that they are indeed adventures of the mind. What, after all, is the good of scientists reproaching others for their neglect of, or indifference to, the scientific style of thinking they set such great store by, if their own writings show that they themselves have no clear understanding of it?

Anyhow, I am practising what I preach. What I have said about the nature of scientific discovery you can regard as being itself a hypothesis, and the hypothesis comes where I think it should be, namely, it comes at the beginning of the series. Later speakers will provide the facts which will enable you to test and appraise this hypothesis, and I think you will find -- I hope you will find -- that the evidence they will produce about the nature of scientific discovery will bear me out."

PART I: The Art of Knowing

> In our endeavor to understand reality we are somewhat like a man trying to understand the mechanism of a closed watch. He sees the face and the moving hands, even hears its ticking, but he has no way of opening the case. If he is ingenious he may form some picture of a mechanism which could be responsible for all the things he observes, but he may never be quite sure his picture is the only one which could explain his observations.
>
> —EINSTEIN AND INFELD, *The Evolution of Physics*

CHAPTER ONE

Science as Metaphor

> At the leading edge of experience in philosophy, science and feeling there is inevitably a groping for language to translate the insecure novelty of noticing and understanding into a precision of meaning and imagery.
>
> —FRANK OPPENHEIMER

OPPENHEIMER WROTE these words in the introduction to a series of readings at The Exploratorium on "The Language *of* Poetry and Science." Poetry and science? Not so strange when you consider that Niels Bohr himself once wrote, "When it comes to atoms, language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images."

Science, after all, involves looking mostly at things we can never see. Not only quarks and quasars but also light "waves" and charged "particles"; magnetic "fields" and gravitational "forces"; quantum "jumps" and electron "orbits." In fact, none of these phenomena is literally what we say it is. Light waves do not undulate through empty space in the same way as water waves ripple over a still pond; a field is not like a hay meadow, but rather a mathematical description of the strength and direction *of* a force; an atom does not literally leap from one quantum state to another; and electrons do not really travel around the atomic nucleus in circles any more than love produces literal heartaches. The words we use are metaphors, models fashioned from familiar ingredients and nurtured with imagination. "When a physicist says 'an electron is like a particle,'" writes physics professor Douglas Giancoli "he is making a metaphorical comparison, like the poet who says, 'love is like a rose.' In both images a concrete object, a rose or a particle, is used to illuminate an abstract idea, love or electron."

Over the centuries the metaphors of science have taken a multitude of forms. Recently, physicists struggling to understand new evidence for a repulsive force in the universe could be heard tossing around terms like "quintessence," "X matter," "smooth stuff," and "funny energy." The more mysterious the emerging landscape, the further they must reach for appropriate imagery to describe it. But there's nothing necessarily odder about this language than the terms scientists have always used to pin down the ineffable.

Here's Francis Bacon's seventeenth-century description of heat: "Heat is a motion of expansion, not uniformly of the whole body together, but in the smaller parts of it, and at the same time checked, repelled, and beaten back, so that the body acquires a motion alternative, perpetually quivering, striving, and irritated by repercussion, whence spring the fury of fire and heat."

And Isaac Newton's account of what we now call chemical reactions: "And now we might add something concerning a most subtle spirit which pervades and lies hid in all gross bodies, by the force and action of which spirit the particles of bodies attract one another at near distances and cohere, if contiguous ... and there may be others which reach to so small distances as hitherto escape observations ... and electric bodies operate to greater distances, as well repelling as attracting the neighboring corpuscles; and light is emitted, reflected, refracted, inflected, and heats bodies; and all sensation is excited and ... propagated along the solid filaments of the nerves."

And Hans Christian Oersteds early-nineteenth-century image of electricity: "The electric conflict acts only on the magnetic particles of matter. All non-magnetic bodies appear penetrable by the electric conflict, while magnetic

bodies, or rather their magnetic particles, resist the passage of this conflict. Hence they can be moved by the impetus of the contending powers."

Compare those with excerpts from a paper proposing a new kind of "dark matter," by physicists Daniel Chung, Edward Kolb, and Antonio Riotto: "The goal of this paper is to show that the Universe might be made of superheavy WIMPs (we will refer to them as X particles), with mass larger than the weak scale by several (perhaps many) orders of magnitude.... To see the effects of vacuum choice and the scale factor differentiability on the large X mass behavior of the X density produced, we start by canonically quantizing an action of the form (in the coordinate $ds^2 = dt^2 - a^2(t)dx^2$)..."

The subjects of science are not only often unseeable; they are also untouchable, unmeasurable, and sometimes even unimaginable. The only way to examine these elusive entities is to scale them up, or shrink them down, or give them a familiar, solid form so that we might finally get at least a temporary handle on them. But even in 1882, physicist and lawyer Johann B. Stallo recognized that the current models of the universe were only "logical fictions," useful tools for understanding but in the end only "symbolic representations" of the real world.

When it comes to science—like so many other things—we find ourselves literally at a loss for words. Thus are metaphors born. When botanist Robert Brown first noticed the quick random motion of plant spores floating in water (now known as Brownian motion), he described it as a kind of "tarantella," according to physicist George Gamow, who went on to anthropomorphize it as "jittery behavior." (Brownian motion was the first convincing evidence for the existence of molecules, since it was bombardment by water molecules that made the plant spores dance.)

Later, Gamow described X rays as a mixture of many different wavelengths of invisible light. "Being suddenly stopped in their tracks [by a target], the electrons spit out their kinetic energy in the form of very short electromagnetic waves, similar to sound waves resulting from the impact of bullets against an armor plate." Thus in German they are called *Bremsstrahlung*, or "brake radiation."

Sometimes the metaphors get confused. A mixture of many colors is called white, but we also call a mixture of sounds "white" noise; we speak of "loud" colors. Something that is "going to seed" is deteriorating, yet "seedy" really means "fertile," since seeds are the origin of new growth. The universe is described alternately as a bubble, a void, or a firecracker. Time is "fluid," or "grainy," or both. Electrons are waves, and light waves are particles. If it all sounds as if the scientists don't know what they're talking about, it is at least in part because a lot gets lost in translation.

Imagining the unseeable is hard, because *imagining* means having an image in your mind. And how can you have a mental image of something you have never seen? Like perception itself, the models of science are embedded inextricably in the current worldview we call culture. Imagine (if you can) what the planetary model of the atom would have looked like, its satellite electrons orbiting its sunlike nucleus, if people had still thought the earth was flat. It would have been literally unthinkable. "A model or picture will only be intelligible to us if it is made of ideas which are already in our minds," wrote physicist Sir James Jeans. It was geneticist J. B. S. Haldane who noted that the inner workings of nature are "not only queerer than we suppose, but queerer than we can suppose."

Unable to suppose what the universe is really like, we rely on our rather limited but comfortably familiar models. The look of those models changes periodically, with the result that our view of the universe changes drastically. It's a long way from Newton's mechanical universe, controlled by invisible pulleys and springs, to today's image of forces as wrinkles in space, of matter as

mere vibrating wisps of energy, of the physical world we know as but a shadow of a higher eleven-dimensional reality. "Scientific theories," writes Isaac Asimov, "tend to fit the intellectual fashions of our times."

Asimov goes on to detail the specific case of the atom, as good an example as any, since atoms are still essentially unseeable—or at least require a completely different kind of seeing than the one we are used to. The Greeks, who specialized in geometry, saw atoms as differing primarily in shape. Fire atoms were jagged, so fire hurt. Water atoms were smooth, so water flowed. Earth atoms were cubical, so earth was solid. Along came 1800, and the world had gone metric—in the sense of being mainly interested in measuring. Shape was no longer interesting; only *amounts* mattered. Thus atoms became featureless little billiard balls, differing mainly in the quantity of mass they contained. Later still, in the 1890s, the fashion in science was the notion of the force field —and so atoms were seen to differ mainly according to the configuration of their outer electron clouds. All these images persist today in one form or another, with physicists still focusing on quantities, organic chemists on the shapes of molecules, and so on.

Another familiar example of this phenomenon is plainly visible in the night sky. The stars in the Northern Hemisphere are clustered into constellations that mirror the images that danced in the heads of the Greeks who named them: All romance and adventure, the stars tell stories of queens and warriors, gods and beasts. The stars of the Southern Hemisphere, on the other hand, were named by a more modern culture, whose main interest was navigation. They did not see bears and lovers in the sky but rather triangles, clocks, and telescopes. "The division of the stars into constellations tells us very little about the stars," wrote Jeans, "but a great deal about the minds of the earliest civilizations and of the mediaeval astronomers."

Of course, it's not surprising that the way we see atoms and stars should change, since images of more everyday things also change drastically from time to time. Any cultures perception of childhood, the role of women, work, religion, government, all look very different in different eras. The ever adorable Judy Garland in *The Wizard of Oz* looks positively fat compared to todays child models.

Metaphors are drawn from common experiences. There is no way to imagine the unknown except in terms of the known, and so the landscape of the unfamiliar gets filled in mostly with familiar images. The images we use to describe both the unseeable subjects of science and the unseen future necessarily are fashioned from the "seeable" world we experience every day. And there's the rub. We do not experience the very large or the very small, the invisible forces and mathematical fields, the curvature of space or the dilation of time. We cannot crawl inside an atom or zoom along at the speed of light. "The whole of science is nothing more than a refinement of everyday thinking," wrote Einstein. But everyday "common sense," he also pointed out, is merely that layer of prejudices that our early training has left in our minds.

Common sense is both necessary and useful. It becomes dangerous only "*if it* insists that what is familiar must reappear in what is unfamiliar," writes J. Robert Oppenheimer. "It is wrong only if it leads us to expect that every country that we visit is like the last country we saw." Yet this is precisely what people do. The truth is that a model, like a foreign language, isn't really useful until you can take it somewhat for granted. It's hard to speak a language fluently when you have to keep rummaging around in the back of your mind for the right word or phrase. And it's hard to understand complicated ideas when the simple ideas and assumptions that lead up to them are still tenuous and elusive. You can't learn much about atoms if you keep having to remind yourself, "Let's see. Now, the nucleus is the thing in the middle. The electron is the much smaller thing on the outside. Is the electron the negatively charged

one? Right, I remember." And so on. Being fluent means having words and ideas on the tip of your tongue. But once you become fluent in a language or in a set of ideas, you have internalized them to the extent that other languages and ideas sound automatically strange and foreign.

"Familiarity is soporific," writes physicist B. K. Ridley. It breeds consent to whatever models we're used to. It's a tender, powerful trap. "Consider the danger of familiarity," he goes on. "It seems clear that an object cannot be in two places at once; but an electron suffering diffraction can. It also seems clear that though size and position are infinitely variable, everything shares the same time; but, as Einstein showed, this is not so. We must check our intuitive ideas all the time."

It's not so easy to check these intuitive ideas, because, well, they're intuitive! Embarking on new territory requires a fresh supply of words and images. But where are they to spring from? Often unknowingly, we keep returning to the same old well. Or as Einstein put it: "We have forgotten what features in the world of experience caused us to frame [prescientific] concepts, and we have great difficulty in representing the world of experience to ourselves without the spectacles of the old, established conceptual interpretation. There is the further difficulty that our language is compelled to work with words which are inseparably connected with those primitive concepts."

In a word, language can easily turn "into a dangerous source of error and deception," Einstein said. Science has a special language problem, however, in that it borrows words from everyday life and uses them in contexts that exist only in realms far removed from everyday life. When I first tried to explain the newly discovered force particles in terms of "the force you feel when you stub your toe," I found that I had stumbled upon a semantic thicket, because "force" on a macroscopic scale and "force" on a submicroscopic scale can masquerade as very different things. Physicists borrowed the idea of force from

Newtons mechanics and applied it to quantum mechanics, where it was modified—at least, to a layperson—almost beyond recognition. How can force have meaning in a system that barely allows for the notion of cause and effect? But still physicists talk about "force particles," and we who were left back with our billiard-ball images of particles and "pushing and pulling" notions of forces stay hopelessly, irretrievably confused.

"Often the very fact that the words of science are the same as those of our common life and tongue can be more misleading than enlightening," says J. Robert Oppenheimer, "more frustrating to understanding than recognizably technical jargon. For the words of science—relativity, if you will, or atom, or mutation, or action—have a wholly altered meaning."

Many physicists are particularly uneasy about terms applied to subatomic particles: "Quark" for example, was borrowed from a phrase in *Finnegans Wake;* in German it means something like "cream cheese." But "quark," to most people, doesn't mean much of anything. Far worse, say the physicists, are those words that do. The subatomic world is teeming with strange species of particles bearing oddly familiar names. "Strange" is one of them. Yet particles called "strange" or "charmed" or variously "colored" or "flavored" are not in any way particularly unusual or pleasant or green or good-tasting. The words are worse than nonsense (say some physicists), because they are downright deceiving.

Physicist Richard Feynman, for example, objected that this was "lousy" terminology: "One quark is no more strange than another quark. Maybe charm is OK, because it's so far out you know it isn't really charmed. But people think that up quarks are really turned up somehow, so it's very misleading." Victor Weisskopf concurs: "I always get the creeps when people talk about virtual particles," he says. "There is no such thing. It's a mathematical concept to describe the strength of a field." The term "virtual" refers to the very short-lived nature of such particles, but even the term "particle," Weisskopf points

out, "is only there to remind you that the field has quantum effects."

It's hardly fair to pick exclusively on modern words like "charm" and "color." Where does a term like electric "charge" come from? Is it like a charge account? A charge in battle? (Obviously the usage "to get a charge out of " something comes from the science and not vice versa.) We speak of positive and negative electricity, when in fact there is no such thing—and if there were, the positive would be negative and vice versa. (Something with a negative charge actually has an excess of electrons, the particles of electric charge. Something with a positive charge has fewer electrons than it needs to make it neutral.) When an atom gets "excited," it does not sit on the edge of its seat (although it may dance around a bit). On the subatomic level, "force" means something closer to "interaction," and the strength of a force becomes the probability of its occurring.

The real trouble with words is that they automatically embody images, whether we recognize this or not. Take the word "wave," for example. It is almost impossible to think of a wave without conjuring up an image of something that looks like a water wave. And for many centuries nobody could figure out what light was, because of this linking of wave to its image in water. Water waves travel through water more or less the way sound waves travel through air and other substances. If light was a wave, it seemed painfully obvious that it had to move through something, too. The painful part was figuring out what that something might be.

As it turned out, no one could find this mysterious substance or even imagine its clearly impossible properties. It was called the luminiferous ether, and from the late seventeenth century until the time of Einstein, people were as certain of its existence as other people had been certain that the earth was flat. Yet in order to vibrate fast enough to carry light, this ether would have to have the properties of a solid. Needless to say, this posed a few problems. "If the all-penetrating ether is solid," writes Gamow,

> how could the planets and other celestial bodies move through it without practically any resistance? And, even if one would assume that the world ether is very light, easily crushable solid material, like Styrofoam, the motion of celestial bodies would bore so many channels in it that it should soon lose its property of carrying light waves over long distances! This headache was pestering physicists for many generations until it was finally removed by Albert Einstein, who threw the ether out the window of the physics classrooms.

Einstein was able to throw out the ether because he threw out the image of a light wave undulating like a water wave. A light wave could travel through nothing at all, because it is made, essentially, of a moving electric field that sets up a moving magnetic field that in turn sets up a moving electric field and so on and so forth—pulling itself up by its bootstraps. Its like an electric motor turning on a generator that turns on a motor and so on. It doesn't need to travel *through* anything because its electric and magnetic fields create each other as they zip along—at 186,000 miles per second, mind you. But its easy to see how the image of water waves hung people up.

There are, of course, many other examples throughout history. Pythagoras's model of planets revolving on invisible spheres became so strongly entrenched in Greek thought that "the Greeks soon seemed unable to imagine any planet without its orbital sphere upon which it moved in a perfect circle," writes author Guy Murchie, "any other orbit being obviously less godly." Harvard biologist Stephen Jay Gould reminds us how hard it was for people to accept the idea of continental drift because it seemed so contrary to current thinking; once it caught on, everybody seemed to think that anyone

who didn't accept it was stupid.

Einstein himself got stuck on his image of an essentially unchanging universe. He even invented something somewhat like the notorious "world ether" to make his model work. It was a mathematical device called the cosmological constant, which would oppose the pull of gravity, keeping the universe still. Later he called it "the greatest blunder of my life." Ironically, recent evidence that the universe may be accelerating at its outer edges suggests that such a repulsive force might actually exist. If so, Einstein was wrong about being wrong. Not surprisingly, physicists struggling to understand this force are inventing a new set of terms to describe it. One of these terms—quintessence—harks back to the original ether, the fifth essence (after fire, earth, air, and water).

Reductio ad Abstractium

Models are as impossible as they are perfect—just like fashion models, superwomen, or Superman. And physics is just as full of perfect but impossible things: ideal gases, perfect crystals, the ubiquitous billiard ball that serves as a model for everything from atoms to stars. A central feature of science is "the process of abstraction," writes Philip Morrison, "the distilling from some bit *of* the real world a more cleanly defined system that will, one hopes, still exhibit the properties of the real system in which he is interested. Much of the excitement that can be found in the practice of physical science has to do with seeking clever abstractions for complicated physical systems and then justifying the choice of the abstraction."

The abstractions of science are stereotypes, as twodimensional and as potentially misleading as everyday stereotypes. And yet they are as necessary to the progress of understanding as filtering is to the process of perception. Science would be impossible without them—if only because the real world of nature is much too complicated to deal with in its natural form. Abstractions are a way to distill the essence from an otherwise unfathomable situation.

"Physics is about the simple things in the universe," notes one physicist, and yet "it could be argued that simple things plainly do not exist." Biology and chemistry are incredibly complex compared with physics, but even such a seemingly simple thing as a stone, he says, is "much too complicated for a physicist to deal with."

The simpler the models, the more removed they are from reality. Yet the simplest models are often the most useful ones. That's one reason that math is such a powerful tool in physics. Its the ultimate abstraction, which cleanly takes care of many of the messy details of reality by temporarily dispensing with them altogether. All models, in a sense, are intermediate steps on the road to mathematical abstraction. "The imagery allows us to move forward more rapidly, but the truth is in the math," explains Caltech physicist Kip Thorne.

As British psychologist Richard L. Gregory puts it, the images are a kind of "cartoon-language." He notes, "Just as the pictographs of ancient languages become ideograms for expressing complex ideas—finally expressed by purely abstract symbols as pictures become inadequate—so such models become restrictive. They give way to mathematical theories which cannot be represented by pictures or models."

Today mathematics has become very much the language of science. The objects of study are mathematical and so are the models and even the metaphors. I was surprised to hear theoretical physicist David Politzer of Caltech describe the most recent inventions in the physics of the early universe—

the moments just after the Big Bang—as mathematical theorems. "English is just what we use to fill in between the equations," he said. "The language we use to talk to each other doesn't have analogies in nature. But we have greatly extended our mathematical vocabulary, and we are always looking to expand this set of metaphors. That's what it's all about: Understanding is a way of picturing things, and mathematics gives you a way to do it."

Politzer, like so many others, insists that the real stuff of physics is essentially nontranslatable into everyday language. But this isn't so unnerving once you consider that it's impossible to experience almost anything beyond a superficial level until you learn its special language, whether it's tennis or ballet or law. Like any other jargon, math is a vehicle that lets you go a great deal farther than you could go without it. (My friend the physicist once gave as an example of the usefulness of jargon the phrase "second cousin twice removed." Although it does not mean much unless you know the jargon of family relations, it is certainly a lot simpler to say, "Frieda is Mike's second cousin twice removed" than it is to say, "Mike is the great-great-grandson of the man who is Frieda's great-great-great-grandfather." Sailors are also well aware of the usefulness of jargon. Once I was sailing with a boatload of novices, and we were about to run aground. The skipper ordered everyone to hike out over the lee rail. About half the crew went to port while the other half scampered to starboard.)

Math is particularly useful jargon in that it allows you to describe things beautifully and accurately without even knowing what they are. You can forget about the problem of trying to imagine the unimaginable in everyday terms, because you don't need to. "The glory of mathematics is that *we do not have to say what we are talking about,"* writes Feynman (emphasis his). Curiously, these mathematical images often come closer to describing reality than images fashioned from reality itself. And as many discoveries have been made in physics by looking at equations as by looking through microscopes and telescopes. “There is a mystery to this,” says Feynman, “how mathematical thinking seems to make things fit.” Unfortunately (or perhaps fortunately), we cannot make a mathematics of the world, as Feynman points out, "because sooner or later we have to find out whether the axioms are valid for the objects of nature. Thus we immediately get involved with these complicated and ‘dirty’ objects of nature, but with approximations ever increasing in accuracy.”

It is not so surprising that when the mathematical models get dressed in the metaphors drawn from everyday experience, we get into trouble. “The history of theoretical physics,” wrote Sir James Jeans, “is a record of the clothing of mathematical formulae which were right, or very nearly right, with physical interpretations which were often very badly wrong.” Newtons laws of motion were almost entirely right —*entirely* right *if* you neglect such extreme instances as travel at the speed of light. Yet when they were interpreted as the inner workings of a giant mechanical clockwork that existed in absolute space and time, they “put science on the wrong track for two centuries.” In the same way, the mathematical formulas describing the interaction of electric and magnetic fields (light) went wrong only when they were interpreted as the undulation of light waves through the world ether.

sorMathematical or otherwise, our images of nature are always bound to be somewhat wrong. But even inaccurate mental models can be useful. A young physicist I know believes that it is bad to introduce people to atomic structure by letting them imagine electrons in orbit around a nucleus like planets around a sun. The model is wrong, he argues. But all *of* us (including most scientists) begin the journey to the center of the atom with this comfortably familiar image; only later did physicists embellish it with the subtle complexities of quantum states. The orbits are a temporary framework that helped peo-

ple to get their footing while climbing toward a higher level of understanding. As J. Robert Oppenheimer writes about his "house of science": "It is not so old but that one can hear the sound of the new wings being built nearby, where men walk high in the air to erect new scaffoldings, not unconscious of how far they may fall.”

Scotsman James Watt constructed a workable steam engine in the eighteenth century based on an incorrect theory of heat. A hundred years later another Scot, James Clerk Maxwell, constructed a theory of electrodynamics based on "a lot of imaginary wheels and idlers in space,” writes Feynman. "But when you get rid of all the idlers and things in space, the thing is OK.” Physicist P. A. M. Dirac first predicted the existence of antimatter by imagining holes in empty space. Antimatter turned out to be real enough, even though the holes didn’t.[3]

Sometimes models that no one takes seriously turn out to be surprisingly real. When it was first developed, the image of a force field was just a pretty picture. "In the beginning,” write Albert Einstein and Leopold Infeld, “the field concept was no more than a means of facilitating the understanding of phenomena from the mechanical point of view.” Yet before long the field took on an unexpected reality. The physicists conclude, “The electromagnetic field is, for the modern physicist, as real as the chair on which he sits.”

Models are stepping-stones, just as Einstein built on the structure erected by Newton, so Newton built on that of Kepler and Copernicus. (If Copernicus had not published his *treatise* on the heliocentric solar system, if Kepler had not precisely calculated the elliptical paths of the planets, Newton could never have seen the similarity between their motions and the fall of the apple.) A model can serve as a solid foundation even when that model is assumed to be wrong. Maxwell himself apparently didn’t believe in the popular model of an electrically charged atom. “It is extremely improbable that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges," he wrote, "for then we shall have obtained a secure basis on which to form a true theory of electric currents and so become independent of these provisional hypotheses."

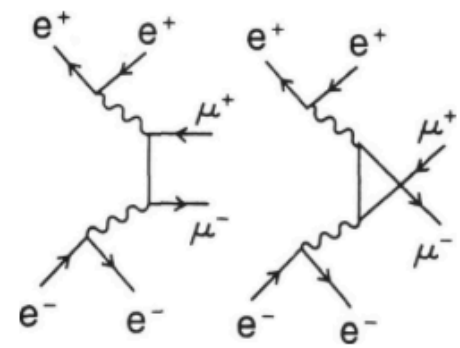
Seeing Through Images

There is a more fundamental reason for using models, however, even when these mental images of things are inevitably blurry compared to the more measured terms of mathematics. We visualize because "seeing" is inextricably linked with understanding. ("I see" is synonymous with "I understand.") Visualizing helps us think about the unthinkable. Sometimes nature is unthinkable because it's so complicated. "In one chunk of ordinary material you have 10^{23} atoms," says physicist Marvin Goldberger. "Even if you had a computer that could deal with that many interactions, you still couldn't imagine it. Even if it were practical, it wouldn't be useful. So we go back and forth, between the words and the pictures."

At other times, nature is unthinkable because it is so far removed from our everyday experience. Trying to picture the universe before the beginning of time or beyond the boundaries of space confronts us with the unimaginable. (We may be able to think about *when* the Big Bang was, for example, but *where* was it?)

Feynman understood the importance of visualization as much as anyone, despite his repeated insistence that some things can be understood only through the language of mathematics. Feynman, after all, was a master visualizer. His Feynman diagrams are a visual language for describing complex sub-

atomic events as a collection of simpler ones. In the early 1980s, I got the rare opportunity to sit down and talk with him about how he *thought* about physics. His response was, as usual, enlightening:



Feynman diagram

We learned something from Einstein. He wanted to put those two pieces together (electromagnetism and gravity, as part of the effort to find a common link among all the forces of nature) and he failed, partly because he started too early. It was like trying to put together a car when you only have two pieces. Today we have many more pieces of the puzzle, and the puzzle is much more complicated.

But he also failed—of course, I don't know why Einstein failed—but when he did his early work, he visualized a lot. A guy going up in a spaceship sending light back and forth (which helped him "see" the true relationship between time, distance, and the speed of light); a guy going up in an elevator (which helped him see that gravity and acceleration were equivalent). He got the idea that way, and then he formed elegant equations to explain the idea. He was good at it. It was nifty.

> Later, when he was searching for a unified theory, he used a different kind of thinking—a guessing at mathematical forms. For years I've tried that and have fallen on my face. So I'm trying to do it visually. [The Feynman diagrams] aren't sufficient for this so I'm searching for a new descriptive imagery. I'm trying to follow my own advice.

The problem that Feynman was working on at the time was the nature of the mysterious force that binds quarks and their "force particles," gluons, inside atomic particles.[4] He explained how he liked to take "the most odd, peculiar, striking" thing about the problem and abstract it away from the rest. In the case of quarks, the most striking thing is that the color force increases as the quarks get farther apart. "So you ask," said Feynman,

> What's the simplest way of stating it? How can you make a simpler problem with the same peculiarity? Say I use only two gluons, forget about the quarks. Assume that space is twodimensional. If I try the theory with only two colors and no quarks and two dimensions, I think I understand why the gluons don't come apart. Now I have to climb back up and put the quarks back in and see if it still works. I may have thrown out the baby with the bathwater in trying to simplify, but I don't think I did.

Throwing out the baby with the bathwater is always a problem with building models, because models are always abstractions. One never knows for sure whether the model has really gotten to the essence of things or just gotten rid of it. And if the kinds of stereotypes we have constructed of people are any guide, the answer is not encouraging. In most cases, we have skimmed the

surface while leaving the deeper reality untouched.

"To what extent do models help?" asked Feynman. "It is interesting that very often models do help, and most physics teachers try to teach how to use models and to get a good physical feel for how things are going to work. But it always turns out that the greatest discoveries abstract away from the model and the model never does any good."

Scaffolding is only a façade. Eventually even the strongest scaffolding gets cast aside and the best models are replaced by newer ones. Einsteins relativity replaced the luminiferous ether; the Bohr atom refined Ernest Rutherfords miniature planetary model by combining it with a musical image of standing waves. Scaffolding is a great support from which to build and remodel and fine-tune, but the trick is remembering that it's not the real thing.

And taking models too literally can lead us into hopeless and unnecessary confusion. People often get frustrated in their attempts to learn about atoms, because the image of everyday "particles" is so indelibly (and perhaps unconsciously) imprinted in their brains. It's natural to want to know just where an electron is—or, in the case of radioactivity, just where the electron was hiding in the nucleus before it was emitted. Just where are the electrons in an atom during the transition between one quantum state and another? (Just where are they at any time?) And which electron occupies which quantum "orbit"?

But this way of thinking about electrons, Jeans points out, is akin to believing that your bank balance actually consists of so many coins in a particular pile. When your balance changes by a certain number of dollars, you don't imagine those dollars actually flying through the air from, say, your account to that of the department stores whose bills you just paid. You do not worry about which particular dollars pay for the rent or the groceries. If you insisted on trying to put your finger on these pieces of information, you would hear yourself talking very much like a physicist talking about electrons: You would have to say that which particular dollars pay the rent is largely a matter of chance. This, says Jeans, "may be a foolish answer—but no more foolish than the question."

Models can also be misleading when used in inappropriate contexts—say, when simple models of physics are applied to complex things like people. As Stephen Jay Gould points out, "a machine makes a poor model for a living organism. Physical models often imply simple, inert objects like billiard balls that respond automatically to the impress of physical forces. But an organism cannot be pushed around so easily." Yet we talk about "the force of habit" or "the pressure to achieve," as if we were just as inert as billiard balls. We speak of "balance of power," as if we knew how much power weighed and how to measure it. We speak of "forcing" people or nations to do things, as if we knew which buttons to push to make them go and make them stop, as if there were only a single possible response to our actions.

In the end, models and metaphors are useful only to the extent that we understand their meaning and limitations. It does not do any good to understand atoms in terms of billiard balls if we don't understand billiard balls, or motives in terms of forces if we don't understand forces. As Jeans puts it, "Nothing is gained by saying that the loom of nature works like our muscles if we cannot explain how our muscles work."

CHAPTER TWO

Right and Wrong

> We may need to rely again on the influence of science to preserve a sane world. It is not the certainty of scientific knowledge that fits it for this role, but its *uncertainty*.
>
> —STEVEN WEINBERG (emphasis his), *Dreams of a Final Theory*

SOME YEARS AGO, I was invited to speak to a group of "gifted" junior high school students in our community on the subject of science and creativity. Thinking that nothing could be quite as creative as Einsteins theory of relativity (what could be more creative than refashioning our fundamental notions of matter, space, and time?), I decided to try them out on that. All went well until the end, when a girl sitting way in the back asked, "But what if Einstein was wrong?"

What indeed? It was a fair question, to be sure. Science seems littered with the mostly forgotten remnants of "wrong" ideas. Heat is not a fluid; the earth is not flat nor does it reside at the center of the universe; the planets do not revolve in perfect circles on fixed celestial spheres; Mars is not covered with canals; no luminiferous ether pervades our space, undulating invisibly as a carrier of light. On the other hand, empty space is now described as curved into four (or more) dimensions, and even vacuums are said to come in several exotic varieties. It seems that the outrageous ideas of yesterday are the scientific facts of today—and vice versa.

In the past few years alone, science has suffered a surfeit of well-publicized

WHAT REALLY MAKES A GOOD STORY?

STORYTELLING has become one of the most popular techniques of marketing communication. ***It's a very effective way to engage audiences, convey information and influence people without using overt persuasion.*** This graphic shows the characteristics of great stories, as found by academic researchers and professional writers.

TRUST IN THE TELLER

Our feelings about a storyteller influence our reaction to their story.

Don't censor the drama of a real-life story. Taking out the 'bad bits' damages trust.

DRAMA

Stories need dramatic development and emotional dynamics.

Real life has ups and downs, so people relate to stories with drama.

RELATABILITY

The more people identify with a story, the more likely they are to be persuaded.

People are drawn into stories they can relate to.

IMMERSION

The more readers put themselves into a story, the more likely they are to change their opinions.

It's usually the simplest stories that entrance us most.

SIMPLICITY

Simple stories are strong stories. Take out everything that doesn't serve the narrative.

Tell a simple story so people reach the conclusions you want them to.

AGENCY

Stories are most persuasive when readers work out their meaning for themselves.

It's easier to fill in the gaps if a story is familiar.

FAMILIARITY

The more familiar a story feels, the more powerful it is.

Familiar stories are trusted. Unfamiliar stories may have to work to establish trust.

For a full discussion of the ideas and research summarised in this infographic, please visit abccopywriting.com/goodstory

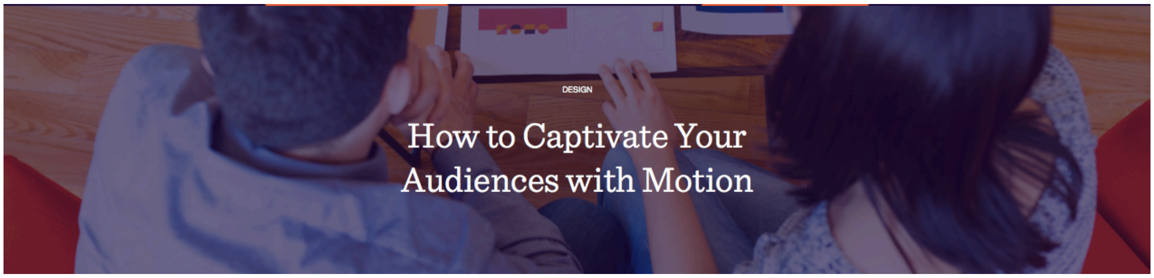
ABC Copywriting

“Literature, though, not only delights but instructs. The computer scientist Jerry Hobbs has tried to reverse-engineer the fictional narrative in an essay he was tempted to call “Will Robots Ever Have Literature?” Novels, he concluded, work like experiments. The author places a fictitious character in a hypothetical situation in an otherwise real world where ordinary facts and laws hold, and allows the reader to explore the consequences. We can imagine that there was a person in Dublin named Leopold Bloom with the personality, family, and occupation that James Joyce attributed to him, but we would object if we were suddenly to learn that the British sovereign at the time was not King Edward but Queen Edwina. Even in science fiction, we are asked to suspend belief in a few laws of physics, say to get the heroes to the next galaxy, but the events should otherwise unfold according to lawful causes and effects. A surreal story like Kafka’s Metamorphosis begins with one counterfactual premise—a man can turn into an insect—and plays out the consequences in a world where everything else is the same. The hero retains his human consciousness, and we follow him as he makes his way and people react to him as real people would react to a giant insect. Only in fiction that is about logic and reality, such as Alice’s Adventures in Wonderland, can any strange thing happen.”

“Fiction is especially compelling when the obstacles to the protagonist’s goals are other people in pursuit of incompatible goals. Life is like chess, and plots are like those books of famous chess games that serious players study so they will be prepared if they ever find themselves in similar straits. The books are handy because chess is combinatorial; at any stage there are too many possible sequences of moves and countermoves for them all to be played out in one’s mind. General strategies like “Get your Queen out early” are too vague to be of much use, given the trillions of situations the rules permit. A good training regime is to build up a mental catalogue of tens of thousands of game challenges and the moves that allowed good players to do well in them. In artificial intelligence, it is called case-based reasoning.”

“Life has even more moves than chess. People are always, to some “extent, in conflict, and their moves and countermoves multiply out to an unimaginably vast set of interactions. ... The intrigues of people in conflict can multiply out in so many ways that no one could possibly play out the consequences of all courses of action in the mind’s eye. Fictional narratives supply us with a mental catalogue of the fatal conundrums we might face someday and the outcomes of strategies we could deploy in them.”

Excerpt From: Pinker, Steven. “How the Mind Works.” Penguin Books Ltd,



There is a part of the visual cortex called MT that governs motion perception, making the human brain uniquely responsive to movement. We find it fascinating and stimulating. We gleefully use GIFs to convey just the right emotion, catch ourselves glued to moving screensavers, and who doesn't love movies?

With a background in neuroscience, ballet and design, I find that motion is always on my mind. In fact, it's on all of your minds too, albeit subconsciously. We all experience proprioception, an awareness of where each part of our bodies exists in space. Ballerinas are rigorously trained in proprioception. With it, they are able to execute extraordinary athletic feats with effortless poise. Designers experience something similar when orchestrating how a brand's visual assets move. They have a specific vision for when, where, and how all the pieces move and interact in a space.

Motion communicates across disciplines. If we look at motion in neuroscience, dance and design, it's just information displayed on different canvases: the brain, the stage or the screen, respectively. Activation in the brain is visualized via the BOLD (blood oxygen level-dependent) signal as blood dances from one brain region to the next as we think about and do different things. Choreographers transport us to other worlds by moving dancers on and off the stage and around each other. Motion designers create narratives by tweaking transitions and moving graphic elements around the screen.

[…]

Motion is everywhere, and because we are so attuned to it, it becomes a powerful tool to engage and inform. With that in mind, how can we infuse motion into communications and create more dynamic experiences across all media […] Here are a couple principles I find helpful for crafting experiences that excite and connect with audiences on a very human level.

1. RHYTHM

We have an innate ability to discern pace. When objects don't behave according to the laws of physics, it makes us uncomfortable. For example, when a large object falls more slowly than a small one, it feels strange to the viewer. We may not be able to articulate why, but motion at unnatural speeds turns us off. Don't create anxiety for your audience.

Rhythm in motion design speaks to what feels comfortable to the viewer in terms of speed. What if you suddenly started experiencing the world in time lapse? It would be so stressful, living life in fast forward. Don't put your audience in that position, and disseminate information at a comfortable pace.

The New Yorker is a publication that sets a pleasant rhythm. By establishing a hierarchy of visuals and information, they control pace. Headlines appear at the top of the page of copy and are bigger than the rest of the text so we read them first. Little cartoons interrupt long columns of text to provide pauses and comic relief.Remember, the rhythm you create — that strategic timing and placing of elements not only makes a more varied experience, but also a more enjoyable one.

THE NEW YORKER

FAMILY TREE
NUDE DUDE

Kenny R. Burck, semi-retired, a large man with the looks of a hard-eyed, towheaded boy, took his seat on the dais at the Golden Anniversary Banquet of the Ohio Genealogical Society at a resort hotel in Huron, Ohio, and, turning to the keynote speaker, who was on his right, asked, "How many other people do you know named Ian, besides yourself? Is that getting to be a more common name these days? It's Scottish for John, right? Now, my last name, Burck, people sometimes think is the English Burke, with an 'e,' but it's not, it's German, and there should be an umlaut over the 'u,' but of course we don't use umlauts in America. I've traced the Burcks back to 1560 in northern Baden, in Germany. My Burck ancestors in America came to Cincinnati ... ert Burck, my son, born December 23, 1970. Recently, a New York tourism bureau announced that the Naked Cowboy is the third leading tourist attraction in New York City, after the Statue of Liberty and the Empire State Building. Not a lot of fathers can say that about their son, can they?"

The salad course arrived. "How did your son get to be the Naked Cowboy?" the keynote speaker asked.

"Well, it wasn't easy, and it didn't hap- ... sters, the way your struggling artists do. He got some small parts, a non-speaking part on 'Baywatch,' for example, but he's a perfectionist in everything he does and he wasn't satisfied with how the acting was coming along. So then he decided to become a country-and-Western singing star. Well, in just a few weeks he'd gotten pretty good at the guitar, and he started writing his own songs. He adopted the country-and-Western look—the cowboy hat and the boots, along with clothes, too, at that time.

"He was travelling around the country for a few years, playing mostly on the street—places like Key West, Florida, and Venice Beach, California—and one afternoon he was playing and singing on Venice Beach, also known as Muscle Beach, and he wasn't getting much of a crowd, and a photographer friend of his suggested he take off his clothes and sing, and since it was a hot day, what the heck, he did take off his clothes, and, sure enough, he drew a big crowd and made a lot of money. This photographer said, 'Hey, you're the Naked Cowboy,' and that's how it all started. Then ten years ago he came ... boy, I sure did drag him around to a lot of libraries and cemeteries and so on in my own researches, and maybe that contributed to his mental illness so he wanted to stand in his jockey shorts playing the guitar in front of strangers on the street. I'm kidding—the Naked Cowboy isn't mentally ill, he's as sane as you or me. He says he used to travel the country to meet a million people, but now millions come to New York City every year to meet him. People sometimes tell him they know him from somewhere or they're a friend of his dad. The way he'll know you're really a friend of mine is if you tell him you met me and then say the one word: 'genealogy.' That way the Naked Cowboy will know you are for real."

—Ian Frazier

HOSPITALITY DEPT.
SHOP TALK

... ish sauce (Porter House New York). Listening to the concierges talk shop felt faintly like a trespass, akin to running into one's high-school principal at a movie theatre. "A lot of the hot things that are out there now only take reservations by e-mail—Monkey Bar, the Waverly Inn, Momofuku Ko," Mootz said. "It's really annoying. What do I say to my guests who want to go during prime time?"

As Mootz was recalling a "pizza binge" he had recently set up for a guest and her teen-age son, Len Feiner, from the Hilton Short Hills, approached. New Jersey, he said, didn't always challenge a concierge. "It's basically corporate during the week, and on the weekends it's weddings," he said. "Wedding parties don't need anything. So I miss that."

Feiner, who worked for years at the Crowne Plaza, used to send his guests to Joe Allen, on Forty-sixth Street.

"I still haven't been there!" Mootz said. "I give them so much business they called and asked me to check it out myself."

"Sit at Table 18," Feiner said. "I have the meat loaf."

... for—what's that comedy with James Gandolfini? 'Dogs' something. 'Dogs of War.'" (He meant "God of Carnage.")

Two of his co-workers appeared with drinks, and they toasted their hotel, which was framed by a large window overlooking Columbus Circle. When McFadden pulled out a business card, one of his colleagues said, "Look at the newbie with the cards."

Over at the Tumi booth, John Morales, the residential concierge at the Ritz-Carlton, was examining a "supercharger" that could charge a phone five times before needing to be recharged itself. (Chargers are to concierges as matchbooks used to be to maître d's.) "This is awesome," Morales said, of the event. "It's like the Emmys. All these businesses giving us these wonderful trinkets. Relaxation is important, because everything is mental power."

Most Thursday nights, Morales gets together with four or five concierge buddies—"the Ritz, the Pierre, my friends in the Marriott"—to smoke cigars at Davidoff or De La Concha. "When we're smoking a good cigar, we talk about 'Oh,

2. EASE-IN + EASE-OUT

Every project should have a beginning, middle, and end. Your audience will feel gratified after having completed the 'journey'. Don't leave the user hanging.

Both ease-in and ease-out help motion designers create movement that obeys the laws of physics and generates a feeling of wholeness. An object at rest needs time to accelerate, reach its peak, and then decelerate. On a larger scale, the entire piece, including audio, should seamlessly ease in and out. Make sure you have a satisfying build, climax, and ending. […]

3. CONTEXT

A piece might have many moving elements, but it should always be very clear what the focus is. Let your audience know who or what is important.

Context focuses the viewer. A film might have many characters, but it's always clear who the protagonist is. Even though multiple interactions occur between the main and supporting characters, which create secondary and tertiary storylines, at the end of the day the focus is still on the protagonist.

The most effective stories on *Medium* strike a balance between providing context and making a point. By introducing the background, the author emphasizes why the chosen subject matter is important, but by limiting it to context keeps the piece on track. The takeaway is the writer's opinion alone.

Giving context comes down to being very clear what your message is, so that it doesn't get lost on your audience.

4. ANTICIPATION

Set up some rules for your experience. They might dictate how objects move or when they appear, and they help your audience learn how to move through the experience. Let people know what's coming.

Motion designers use anticipation to cue the viewer by setting up a visual expectation or pattern. In title sequences, text that appears in specific areas causes the viewer to look there without realizing it. Text can also transition in a certain way over and over again so that viewers can anticipate that specific movement. Sticking to rules that you create prevents your audience from frantically searching for where or how the next piece of information will appear.

I'm sure most of you have played or heard of *Monument Valley*. If you haven't, you absolutely should, because the graphics are simply beautiful. The point of the game is to help Ida, the silent princess, find her way through the monuments. How do you know when you've mastered a level? Ida always takes an orb out of her hat that spins and grows larger to transition to the next level. When you see that orb, you feel a sense of accomplishment, it's positive reinforcement to keep playing. […]

5. CONSISTENCY

You should think about the components of your projects as living within a brand or design system. Doing so will keep things cohesive and give the impression of a more thoughtful and comprehensive experience. Stick to your rules and keep the audience immersed.

In motion design you're creating imaginary environments. Sometimes the whole environment is visible and sometimes you're just providing a glimpse. Whatever the case, by adhering to the rules you create, such as confining objects to the boundaries of the screen or allowing them to float out of view, you avoid confusion and tell a better story.

Sleep No More is a fantastic example of immersive environment design. Every element of the "play", from costumes, actors, set and lighting, down to the papers on the desks and the specimens in the jars, creates a certain look and feel. The entire McKittrick Hotel is part of the experience. From the minute you step into the elevator to the moment you leave the building, how you're treated amongst the immersive surroundings makes you believe that you're in another world.

Consistency requires a full commitment to a framework and makes the experience far more impactful.

6. SURPRISE

Surprise takes what is expected and subverts it. It can be as complex as turning an anticipated emotional response on its head, or as simple as changing size or color of text. The aim is to elicit a positive emotional response to delight the audience.

Motion designers use surprise like a secret weapon. It can drive home the climax, or it can create a break between sections. Sometimes elements travelling one way will suddenly switch direction, or an unexpected swatch of color swipes across the screen to signal a change. […]

Surprise can have a lasting impact. It can even draw in audiences outside your target demographic. […] Motion is a visual language that speaks uniquely to audiences. It can make them laugh or cry, and they'll remember your campaigns for it. By employing motion in your communications, you can create meaningful experiences that incite a visceral response. […]

Openness to Experience

> By replacing fear of the unknown with curiosity we open ourselves up to an infinite stream of possibility. We can let fear rule our lives or we can become childlike with curiosity, pushing our boundaries, leaping out of our comfort zones, and accepting what life puts before us.
>
> —Alan Watts

Around the time that his cult classic drug-culture novel, *Naked Lunch*, was released, beat writer William S. Burroughs was experimenting with a new writing strategy that he called the "cut-up technique." It's exactly what it sounds like: Burroughs would cut up random lines of text from a page and rearrange them to form new sentences, with the aim of freeing his mind and the minds of his readers from conventional and linear ways of thinking, and allow the mind to see things in a new light.

Like Burroughs, the Beat Generation as a whole sought to dismantle old belief systems and to encourage ways of looking at the world. In post-war 1950s America—when conformity was a defining characteristic of American culture and open-mindedness an act of rebellion—the Beats celebrated intellectual exploration, engagement in art and music, unconventionality, and deep spiritual questioning. As America made its way into the disruption and free-spiritedness of the 1960s counterculture, it was as if the collective consciousness had opened itself up to the new and unfamiliar.

In 1952, writer John Clellon Holmes first introduced the "beat generation" to the world, describing the movement as being characterized by "nakedness of mind, and ultimately, of soul." The Beats were a sort of reincarnation of the so-called Lost Generation of the 1920s, although, he said, "the wild boys of today are not lost." What they were instead was *curious*, a generation with "a greater facility for entertaining ideas than for believing in them."

Jack Kerouac, the Beat Generation poster boy whose novels have become manifestos for adventure and nonconformity, perfectly embodies the spirit of openness to experience. The revelations of Kerouac and other Beat writers do shed light on an essential rule of creativity: We *need* new and unusual experiences to think differently. In fact, cultivating a mind-set that is open and explorative might be the best thing we can do for our creative work. As Kerouac said, "The best teacher is experience."

We *need* new and unusual experiences to think differently.

For not only artists but innovators of all stripes, new experiences provide the crucial tissue of real-world material that can be spun into original work. Openness to experience—the drive for cognitive exploration of one's inner and outer worlds—is the single strongest and most consistent personality trait that predicts creative achievement.[1] Openness to experience, one of the "Big Five" personality traits, is absolutely *essential* to creativity. Those who are high in openness tend to be imaginative, curious, perceptive, creative, artistic, thoughtful, and intellectual.[2] They are driven to explore their own inner worlds of ideas, emotions, sensations, and fantasies, and outwardly, to constantly seek out and attempt to make meaning of new information in their environment.

While openness as a personality trait hinges on engagement and exploration, it's also far more complex and multifaceted than that. Openness to experience comes in many forms, from a love of solving complex problems in math, science, and technology, to a voracious love of learning, to an inclination to ask the big questions and seek a deeper meaning in life, to exhibiting intense emotional reactions to music and art. Visionary tech entrepreneurs, world travelers, spiritual seekers, and original thinkers of all types tend to be have highly open personalities.

Research conducted by Scott for his doctoral dissertation suggests that there are at least three major forms of cognitive engagement making up the core of the openness domain.[3] *Intellectual engagement* is characterized by a searching for truth, love of problem solving, and drive to engage with ideas, whereas *affective engagement* has to do with exploration of the full depths of human emotion and is associated with a preference for using gut feeling, emotions, empathy, and compassion to make decisions. Finally, those who are high in *aesthetic engagement* exhibit a drive toward exploring fantasy and art and tend to experience emotional absorption in beauty. Scott found intellectual engagement to be associated with creative achievement in the sciences, while affective and aesthetic engagement were linked with artistic creativity.

Scott's research led him to another fascinating discovery about "open" personalities.[4] The desire to learn and discover seemed to have

significantly more bearing on creative accomplishments than did cognitive ability. He found that people with high levels of cognitive engagement with imagination, emotions, and beauty were more likely to make significant artistic creative achievements than people who were high in IQ or divergent thinking ability (the ability to explore many possible solutions to a problem). Intellectual engagement was sometimes even found to be a better predictor of creative achievement than IQ.

Looking at creativity across the arts and sciences, Scott and colleagues found that openness to experience was more highly correlated with total creative achievement than other factors that had been traditionally associated with creativity, like IQ, divergent thinking, and other personality traits. Together, these findings suggest that the drive for exploration, in its many forms, may be the *single most important personal factor* predicting creative achievement.

Indeed, openness to experience speaks to our desire and motivation to engage with ideas and emotions—to seek truth and beauty, newness and novelty—and the act of exploring often provides the raw material for great artistic and scientific innovations. This engagement starts at the neurological level, with the way the brain reacts to unfamiliar situations and new information. What unites each individual form of openness to experience is an intense desire and motivation to seek new information that is rooted in the individual's neurophysiology and forms the very core of his or her personality.

Fig. 1.1 The basic building bricks of the Universe – the fundamental particles of matter – were formed in the initial hot Big Bang. To learn about these elementary constituents, particle physicists reproduce the energetic conditions of the early Universe with machines that accelerate subatomic particles close to the speed of light, through tunnels kilometres long. The machines are monuments to modern technology. Electromagnets guide the particles repeatedly on circular paths through an evacuated 'beam pipe', part of which is just visible in the bottom right corner of the picture. The beam pipe passes through regions of electric field that provide the accelerating power. This view shows the tunnel of the Tevatron at the Fermi National Accelerator Laboratory (Fermilab), near Chicago, as it looked at the time of the discovery of the top quark in 1994–95, when it contained two rings of magnets. The red and blue magnets (the upper ring) form the Main Ring, which has since been dismantled and replaced by an entirely separate machine. The Main Ring was Fermilab's original machine, which started up in 1972, and from 1985 until 1997 accelerated and fed particles into the Tevatron, the ring of yellow magnets just visible below the Main Ring.

The Executive Lounge at Chicago's O'Hare airport, with its deep pile carpets, soft armchairs, and panoramic view of aircraft manoeuvring, is a temporary oasis for business travellers. The bustle and noise of the concourse disappear once you enter the air-conditioned calm of this living exhibition of state-of-the-art technology. Here you can pause before your flight to enjoy some of corporate America's latest toys. Disregarding the computer screens with their optimistic promises of 'On Time' departures, or the multitudinous channels of worldwide television, you may seek out a glass booth where other travellers' mobile phones will not disturb your business. The booths contain fax machines, modem connections to the Internet for your PC, and optical-fibre links to a mainframe computer should your portable not be up to the task. If you're a television news reporter, you can even make your presentation live through a satellite hook-up.

All of these, and much more to which we give barely a second's thought, are the result of a discovery made more than a hundred years ago by a bowler-hatted, bespectacled Victorian gentleman, Joseph John ('J.J.') Thomson, in Cambridge, England. Every day, among the hordes passing through O'Hare, there are always a few of his modern successors, members of the world-wide network of particle physicists. Take the trio sitting opposite you. They happen to be members of a team whose discoveries have recently completed a chapter in the history of science. They work on an experiment at Fermilab, the 6 km circumference particle accelerator sited 50 km from O'Hare. Their experiment takes place in America, their home universities are in Europe, and their experimental colleagues and collaborators are based in 17 states of the USA, six countries in Europe, plus Canada, China, Korea, and Japan. Their collaboration has enough PhDs to fill a jumbo jet.

The three have been upgraded to Business Class courtesy of their frequent-flyer miles. As particle physicists at large in the twenty-first century, they earn miles so fast that it is hard to unload them and the last thing they want is to take a vacation on yet another flight, even if they could afford the time. For particle physics is big business, the competition global. Managing multimillion dollar budgets and teams of hundreds of PhD researchers, technicians, and engineers is like being

head of a major corporation.

Corporate America is power dressed, with sharp suits and crisply ironed shirts. This uniform distinguishes the businessmen from the physicists, who are dressed as ageing undergraduates, with crumpled check shirts open at the neck, casual slacks or jeans, and their notes carried in overweight shoulder bags that bear the logos of recent international conferences in Singapore, Dallas, or Serpukhov. If their dress hadn't proclaimed their profession, the shoulder bags would, as few people other than physicists visit the Serpukhov laboratory near Moscow.

The trio are like missionaries, returning home bearing the latest news and data from their experiment, which in 1995 made headlines with the discovery of the top quark. This fleeting, minuscule fragment of matter had been eagerly sought for more than 15 years; its discovery was the final piece in the story that had begun with Thomson a century earlier.

Six and a half thousand kilometres east of Chicago, a hundred years back in time, Cambridge was a gas-lit stone city of cyclists. Cycling remains today the fastest way around its heart, where international tourists are disgorged from electric buses to gaze at ancient colleges and visit neon-lit superstores with banks of televisions, all tuned to the same satellite station, which turn a news-reader into a choreographed dance of moving wallpaper. Here, as everywhere, the city and pace of life have changed in ways that J.J. Thomson never foresaw when, in a laboratory in Free School Lane, he discovered the electron in 1897.

Fig. 1.2 (LEFT) Free School Lane, Cambridge, c. 1890, with the old Cavendish Laboratory, where Thomson discovered the electron.

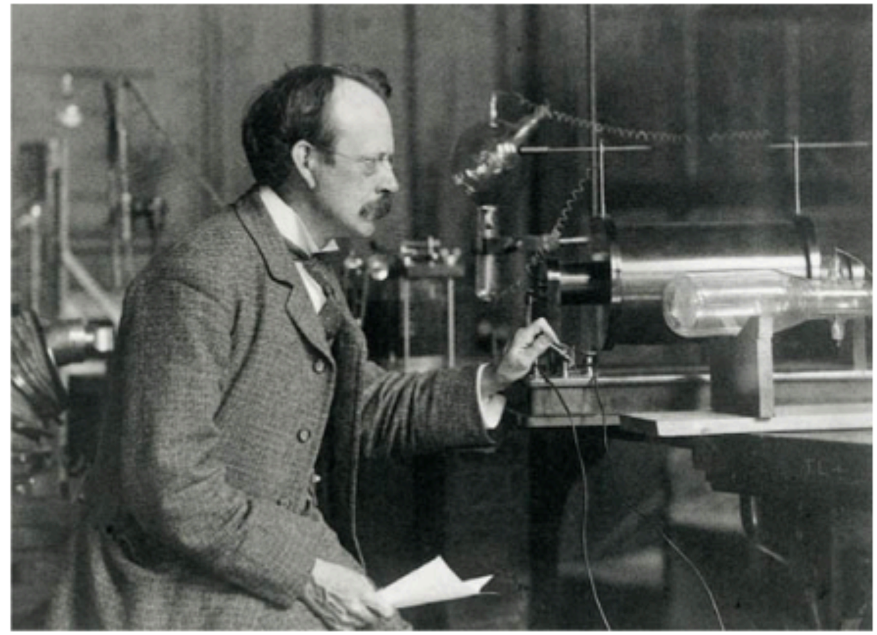


Fig. 1.3 (RIGHT) Joseph John (J.J.) Thomson gives a lecture demonstration of the kind of tube he used to measure the ratio of electric charge to mass for the cathode rays. His results led him to conclude that the rays consist of minute subatomic particles – electrons.

Thomson takes the credit for identifying this workhorse of the modern age and for recognizing that electrons are fundamental constituents of atoms as well as the carriers of electrical current. Like any scientist, he was driven by curiosity. He wanted to determine the nature of the mysterious 'cathode rays', which produced a coloured glow when an electric current passed through a rarefied gas in a glass tube. In his Cambridge laboratory he observed what happened as a narrow beam of cathode rays sped along an evacuated glass tube about 27 cm long to make a glowing green spot at the far end. Using his measurements of how magnetic and electric fields moved the spot, he calculated the properties of the cathode rays and proved that they consisted of particles – electrons.

The electron was the first of what we now know to be fundamental varieties of matter. In the intervening century the list of particles has continually changed as layers of the cosmic onion have been peeled away and deeper layers of reality revealed. Thus nuclei, protons and neutrons, exotic 'strange' particles, and quarks have entered the menu. Throughout, the electron has remained in the list. Today we recognize its fundamentality.

Our best theories require that quarks also are fundamental and that there are six varieties of them, named 'down' and 'up', 'strange' and 'charm', 'bottom' and 'top'. To create the first examples of the top quark, the physicists at Fermilab have had to bring matter and its physical opposite, antimatter, into collision at higher energies than ever before in an underground ring of magnets, 6 km in circumference. The magnets guide protons round in circles as they are accelerated by electric fields; the antimatter equivalents of protons – antiprotons – whirl round the same ring in the opposite direction. As the particles and antiparticles accelerate, their energies increase until eventually they are made to collide head on. Each collision creates a burst of new particles that shoot into giant multilayered detectors surrounding two collision zones. The new particles bear the imprint of events that have happened so swiftly they can never be seen directly. But in 1994–95, the physicists at Fermilab found the 'signatures' expected for the long-

sought top quark.

Fermilab stands on enough grassland to support a herd of American buffalo. The offices of its scientists fill ten floors of a graceful cathedral of glass and stone whose atrium soars up to the roof, is grand enough for trees to grow, and sports a dedicated travel bureau. Prairies stretch for hundreds of kilometres to the western plains. Another land of flat earth, the Fens of East Anglia, is home to the grey stone building with gables and bay windows that is the old Cavendish Laboratory in Cambridge. A rabbit warren of staircases connects the corridors of discovery. Doors open onto small rooms where ingenuity has teased from nature those secrets that are just within reach. No buffalo here, no grand entrances; instead Free School Lane is wide enough for pedestrians and Cambridge's ever-present bicycles. On a misty winter evening today, the illumination can appear hardly more advanced than it would have been in the late nineteenth century. Yet this is where Thomson made his momentous discovery that led to modern particle physics – the science that studies the basic particles and forces and attempts to understand the nature of matter and energy.

Fig. 1.7 The ethereal beauty of the frozen wastes of Antarctica – location of the AMANDA experiment which detects neutrinos that have traversed the Earth after being created in the atmosphere on the other side of the planet.

Cosmic Explorers

The night is already three months old as the aurora flashes across the sky. It is June at the South Pole. Three thousand metres above sea level, and at a temperature of −70 C, a figure wrapped in a parka and thermal underwear lies on the snow watching the natural display while listening to Tchaikovsky's *1812 Overture* on headphones. The person is a particle physicist, one of a team with an experiment at the South Pole, trying to discover how our Universe came to be. Instead of working at huge man-made accelerators, these researchers make use of the natural accelerators in the cosmos, where electromagnetic forces in space whip into violent motion particles from exploded stars and other exotic events. The moving picture-shows of the aurorae occur when particles from the Sun are trapped by the magnetic arms of the Earth and hit the atmosphere. When higher-energy particles from more distant sources smash into the atmosphere the result is an equally dramatic but invisible rain of particles that cascade to Earth. These messengers from the stars show scientists on Earth what subatomic matter is like 'out there'. They have revealed a Universe that is far richer and more mysterious than anyone imagined a hundred years ago.

The particle physicists at the South Pole are working with

AMANDA – the 'Antarctic Muon and Neutrino Detector Array'. This is a telescope, but a telescope that is a far cry from the more familiar structures with lenses or mirrors. Buried under a kilometre of ice, its purpose is to detect not light, but high-energy cosmic neutrinos from our own or nearby galaxies. Neutrinos are mysterious particles that are associated with radioactive phenomena; they have little mass, no electric charge, and are as near to nothing as you can imagine. They travel straight through the Earth as freely as a bullet through a bank of fog. However, they are so numerous in the cosmos at large that they have a significant influence on events in the Universe. They roam the Universe as leftovers of its creation, they are emitted by the processes that fuel the Sun and other stars, and they spill out in huge numbers from colossal stellar explosions.

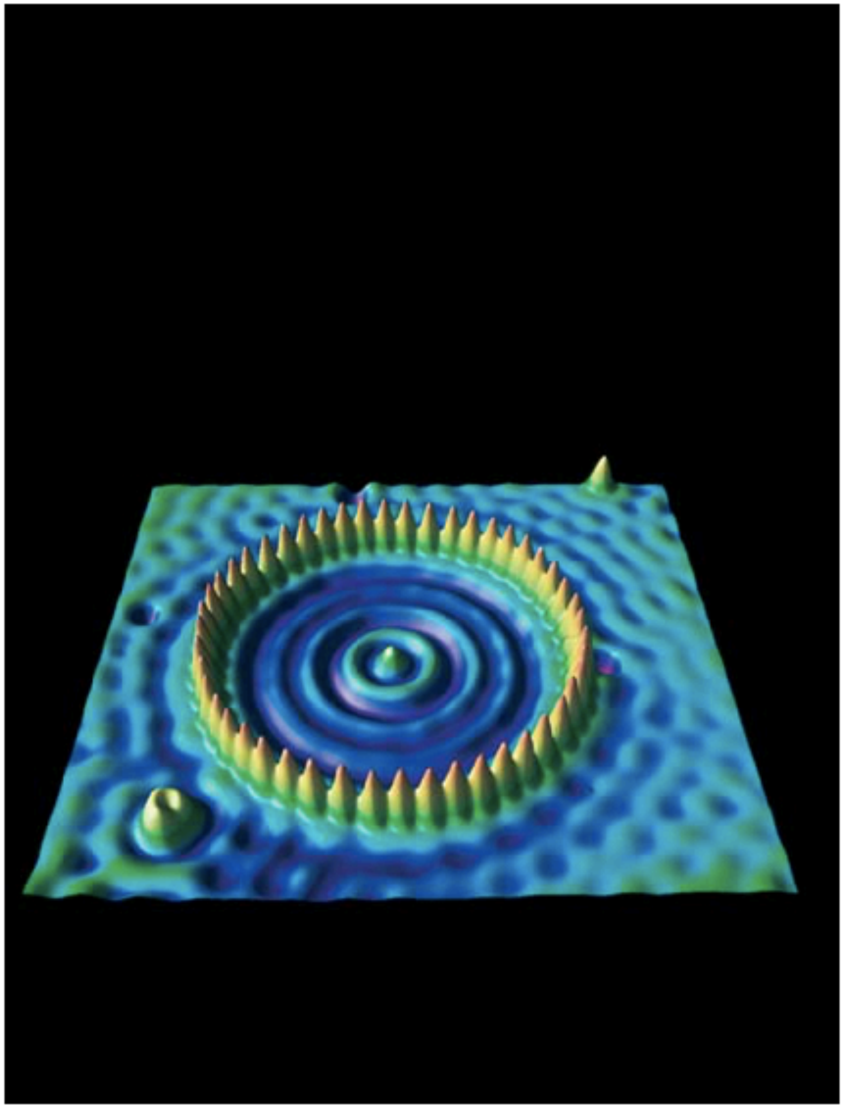


Fig. 2.1 While we cannot distinguish the individual electrons in atoms, we can observe the average effects of their motions. This scanning tunnelling microscope image shows standing wave patterns of electrons in the surface of copper, caused by scattering from the ring of 48 iron atoms. The ring has a diameter of about 14 nanometres (0.000 014 mm).

Take a deep breath! You have just inhaled oxygen atoms that have already been breathed by every person who ever lived. At some time or other your body has contained atoms that were once part of Moses or Isaac Newton. The oxygen mixes with carbon atoms in your lungs and you exhale carbon dioxide molecules. Chemistry is at work. Plants will rearrange these atoms, converting carbon dioxide back to oxygen, and at some future date our descendants will breathe some in.

If atoms could speak, what a tale they would tell. Some of the carbon atoms in the ink on this page may have once been part of a dinosaur. Their atomic nuclei may have arrived in cosmic rays, having been fused from hydrogen and helium in distant, extinct stars. But whatever their various histories may be, one thing is certain: most of their fundamental constituents – the electrons and quarks – have existed since the first split second of the Big Bang. Atoms are the complex end-products of creation.

At the end of the nineteenth century, the existence of atoms was little more than hypothesis. Today the reality of these tiny bundles of matter is accepted as indisputable. We know of many different types of atoms, one for each different chemical element – from hydrogen to uranium – that occurs naturally on Earth; and we have created and characterized in the laboratory atoms of at least 15 other elements heavier

EXCERPTS

Another land of flat earth, the Fens of East Anglia, is home to the grey stone building with gables and bay windows that is the old Cavendish Laboratory in Cambridge. A rabbit warren of staircases connects the corridors of discovery. Doors open onto small rooms where ingenuity has teased from nature those secrets that are just within reach.

Clues to the restless agitation within the atomic architecture are all around us: the radioactivity of natural rocks, the static electricity that is released when glass is rubbed by fur, the magnetism within lodestone, sparks in the air, lightning and countless other clues for those who are prepared to pause and wonder.

Today Fermilab is looking at matter as it was at the beginning of the Universe, including exotic forms that no longer exist but which seeded the stuff we are made from.

The night is already three months old as the aurora flashes across the sky. It is June at the South Pole.

The inner labyrinths of an atom are as remote from daily experience as are the hearts of stars, but to observe the atomic constituents we have to reproduce in the laboratory the intense heat of stars.

If particles are akin to the letters of nature's alphabet – the building blocks from which all else is made – then the analogue of grammar is the set of natural forces that choreograph the cosmos.

Much as an animal leaves tracks in the snow or a jet plane forms trails of condensation across the sky, electrically charged particles leave trails as they gradually lose energy when they travel through a material, be it a gas, a liquid or a solid. The art of particle detection is to sense this deposited energy in some manner that can be recorded. Then, in the way that measurements of the footprints of our ancestors can reveal something about their size and the way they walked, the information recorded can reveal details of a particle's nature, such as its mass and its electric charge.

FRANK CLOSE, MICHAEL MARTEN & CHRISTINE SUTTON