Scientific Curiosity

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Curiosity and Science

*George M. Whitesides**

When I was in—perhaps—4th grade, I heard somewhere that rubber melts when heated. That seemed interesting, and I was curious as to whether it was true. To find out, I poured some gasoline from the lawnmower into an old automobile tire ("rubber") in my family's garage, and set a match to it ("heat"). The tire caught on fire. Also the garage. The fire department came, and all was soon again fine. My parents never mentioned the matter to me—the assumption was that young boys were troublesome, and nothing useful could be done about that. I learned that rubber tires do not melt, but do burn. I also learned that curiosity leads in unexpected directions.

So: what is curiosity? Let me answer by not answering. I am a chemist: my world starts with atoms—nuclei and electrons—and builds everything (or almost everything) from them: from atomic hydrogen, to how the brain thinks. That said, I have never really understood what electrons are, and occasionally I will ask a friendly physicist: "What *is* an electron?" The answer is usually the same: "You can't ask what an electron *is*, only what it *does*". "Curiosity" has the same elusive quality. To shorten Justice Potter Stewart's famous opinion on pornography: "I shall not today attempt further to define the kinds of material I understand to be embraced within that shorthand description … But I know it when I see it…". There are many kinds of curiosity—such a simple word with such a complicated flock of meanings! Curiosity includes Nature, science—and everything else: where geodes come from, human behaviors, the social life of plants, the taste of paprika, perpetual motion machines, the nature of "happiness." It can have the urgency of an absolute requirement (like hunger, thirst, or desire), or flicker on and off as transitory amusements, or settle in as a craving (for tasty new ideas). It can be idle or purposeful, distracted or fixed, naïve or sophisticated. It can be a momentary impulse, or a calculated search extending over years.

Although that question, "What is curiosity?" is really many *different* questions, one can be too pedantic: is it useful for me to disentangle curiosity about life on planets orbiting distant suns, from curiosity about why my wife prefers her coffee with sugar? How is curiosity about physical phenomena different from curiosity about manners, or art, or politics? Curiosity is a wish (or a desire, or an impulse, or a tic, or an obsession) to know more about something (and *some*thing can be *any*thing), often for no particular reason. "Knowing" because it feels good to know. One of its charms is that it comes in so many forms.

My encounter with the tire was an example of *aimless* curiosity. I had no motive other than to see what would happen. What about *scientific* curiosity (or curiosities, since there are many)? What we today call "science" is actually a collection of distinct but related activities, carried out by many kinds of people, with different means and objectives. Curiosity, discovery, invention, understanding, development, application, and "translation to market" are all phases (not necessarily distinct or sequential) in the construction of the technological world. Of these activities, the most muscular are collected under related catchphrases: "science and technology" (S&T), "fundamental understanding and consideration of use" (Pasteur's Quadrant), and "research, development, and engineering" (RD&E). I will call them all "science" to save space, although all are different. This group is analytical, professionally specialized, and not generally given to flights of fancy. "Translation to market" is also analytical, although concerned with business development rather than science. These three are usually activities of groups—sometimes tribal and competitive, sometimes cooperative. Invention and discovery are precursors to "science," (e.g., S&T) and often share many of its organized, analytical characteristics. I think of these activities as a progression: from initial, amorphous interest, to final application in solutions to specific problems.

Curiosity is different. What sets it apart? Even in science, it is more individual than collective, more artistic than scientific, more an itch than a calculation—the most childlike, and personal, part of science, and the least focused on practical goals. It can be entrancing, mischievous, useful, stimulating, (and even dangerous)—it is hard to know where it will lead. It can be aimless, or an arrow pointed toward something worth understanding (and even possibly using). It—like curiosity in areas unrelated to science—is engaged by everything: the mundane, extraordinary, intricate, simple, useful, useless, ecstatic, and horrible. Is it too flighty to be a serious contributor to science? Absolutely "No!" It can illuminate phenomena, and engage reason and emotion, in ways that generate unexpected beginnings and directions. And, to me, simply "knowing more" is always interesting, and almost always a pleasure.

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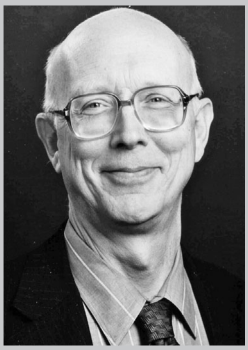
Curiosity in science is also simultaneously an art and a skill: the art of *seeing* (or, perhaps, of *noticing*), and the skill of asking questions. The world is a place of endless marvels, most of which we simply ignore: we see the fact, but skip over the astonishing framework over which the fact is draped. Imagine a Socratic dialog across the most ordinary (and extraordinary) of objects: a glass of water. Question: The surface of the water appears to be flat. Why is that? Answer: Gravity. Q: And what is gravity? A: No clue. Q: And by the way, why is water a liquid? A: Hydrogen bonds. Q: And what exactly is a hydrogen bond? A: Something to do with hydrogen, and oxygen, and electrical charges, or something. Q: And do we understand how hydrogen bonds tie water into a liquid? A: Well, they form networks. Q: Do we understand these networks? A: Really, no. Many weak connections … entropy … complicated! Q: And is water important? A: Sure, we die without it. Q: OK, how about life in general? Can life occur without water? A: No! Q: So, why is water (rather than some other liquid) *required* for life? … And so on.

With me, at least, this process—noticing almost anything, and asking "Why?" repeatedly—always ends in that most optimistic of realizations: "I don't know." (There is yet *more* to think about!) Just trying to trace observable reality back to its origins may seem frivolous—a personal whim, rather than an effort to understand something already identified as important. It also does not seem painful enough to be serious: there are no knotty differential equations, or marathon organic syntheses, or leaky vacuum seals. And yet, for me, this *intentional* form of curiosity works in ways that nothing else does to identify new targets for research.

Curiosity is idiosyncratic. Yours and mine will certainly be different. A spider stalking a beetle fascinates me. (What does the spider see through its multiple eyes? How does that minuscule brain work it all out? Why does the beetle have six legs, and the spider eight?) And by lightning. (What's going *on* in there?) And by megacities (Are they alive? Could they become sentient?) And by magnetism. (What is it, *really*?) Your interests are undoubtedly, and fortunately, different. No matter. Curiosity is not a quiz, and there is no right answer.

It also has the remarkable characteristic that it can be shared—on an almost equal footing—by *people*—by scientists and nonscientists alike. Curiosity requires only observation, and the ability to ask "What's that?" It's a game anyone can play, and even play using different rules. It generates subjects to talk about with the neighbors, and stories amusing for the children and grandchildren. A scientific expert in one subject knows no more than anyone else about a glittering oddity that pops up unexpectedly elsewhere.



George M. Whitesides received his AB degree from Harvard University in 1960, and his PhD from the California Institute of Technology in 1964 (with J. D. Roberts). He began his independent career at the Massachusetts Institute of Technology, and is now the Woodford L. and Ann A. Flowers University Professor at Harvard University. His current research interests include physical and organic chemistry, materials science, biophysics, water, self-assembly, complexity and simplicity, origin of life, dissipative systems, affordable diagnostics, and soft robotics.

For all of this charm, is curiosity *important* in science, or is it just something that we humans do, like blinking our eyelids? Would we be better off—would science, or society, be more creative or more useful—with more or less of it? Curiosity pleases those who have it. It also brings the cool, exciting breath of risk ("Curiosity killed the cat!" The door that it opens could be the top of Pandora's Box?) And while it is one source of new ideas for scientists, it is only one: solving already-defined problems works, too: dealing with the emergency of the moment certainly stimulates creativity. (Thus the tension between "curiosity-driven" and "problem-driven" science.)

Would science dry up without curiosity? I would guess that it would, but not for a long time: there are more than enough pressing practical problems to solve to keep us busy. Vannevar Bush, in *The Endless Frontier* (his post World War II manifesto arguing for federally supported research in the U.S.), listed three justifications for imposing this financial burden on the taxpayer: job creation, national security, and healthcare. These are clear, rational justifications for utilitarian science and technology. Satisfying curiosity was, undoubtedly, tacitly assumed as a benefit, but did not make the first page.

I, personally, take it as a matter of faith that curiosity is essential to science, for its ability to provide fresh ideas, for its requirement to think outside the limits of a particular profession, for its ability to hone the skill of observation, for its ability to provide a common way for people (including scientists), to wonder about the world they inhabit (and the worlds their grandchildren may later inhabit). Some specific examples (see the box) connecting curiosity to science may be useful. I will use personal ones, since curiosity is personal, and they are really the only ones I can vouch for.

The first question (and object of scientific *curiosity*), was the one with which I began when I was a young assistant professor. At that time, the scientific community believed (if it thought about the subject at all) that most carbon–transition-metal sigma bonds would be too unstable to allow the preparation of useful organotransition metal compounds. I was certainly willing to accept this (conceptually plausible) belief, but there were hints in the literature that it might be false. So, out of curiosity, I tried to make a few. Indeed they proved (using a few experimental tricks) to be easily made, and organocopper chemistry ultimately became an active field. These experiments worked, not because I was clever, but simply because I was curious, and no one had seriously tried them before. Curiosity can lead to *terra incognita*!

The last questions on this list—What is life? What was its origin?—are ones to which I am a latecomer. And yet, these are, I would argue, among the most interesting in all of science. I know that molecules are not alive, I know that molecular reactions are not alive, and I know that cells are simply collections of molecules and reactions. But, amazingly, cells *are* alive. How did *that* happen? Do I conclude that "life" is no more than a particular set of organized, dissipative chemical reactions? A particular kind of flame, in which the

Can one make stable carbon-transition metal bonds? (→ Organocopper(I) chemistry)

Can one model heterogeneous metal catalysts with soluble organometallic compounds? (→ Mechanisms of C-H activation by platinum)

Is there another approach to organic synthesis? (→ Cofactor-requiring enzymatic synthesis)

Can one study "soft" (organic) surfaces? (→ Polyethylene surface chemistry, self-assembled monolayers)

How about an easy way to make micro- and nanostructures? (→Soft lithography, microfluidics)

Why is water the universal solvent for life? (→ *Partial* understanding of the hydrophobic effect and entropy/enthalpy compensation)

Is there an alternative to covalent synthesis in making large structures? (→ Noncovalent self-assembly)

What is magnetism? (→Magnetic levitation for analysis)

What are *complexity* and *simplicity* in science (and elsewhere)? (→ A strategy in research)

What is lightning? (→ Electrets and electrostatic self-assembly)

Why is healthcare so expensive? (→ Paper diagnostics)

How to imitate the motions of simple organisms? …and how will humans and robots coexist? (→ Soft robotics)

What are life and sentience, and how did they originate? → (Who knows?)

combustion of glucose and oxygen generates "life"? If true, what about "thought"? Is the same true? And how could life possibly have developed in the violent and chaotic environment of our planet in its early adolescence? A series of How's, What's, and Why's? Confounding, fascinating, and entirely unsolved questions. Also difficult: I will not live long enough to see them all answered (although I can't resist trying to answer at least one)!

Each of the other questions in the box holds a story that is interesting to me, but probably not equally interesting to others. That notwithstanding, to me they suggest several lessons. First, the questions evoked by curiosity, and the research that they nucleated, were usually only casually connected. Curiosity generates starting points, not answers. Second, this list (successes, by my personal definition) slyly omits failures (of which there were more) and the much, much larger number of questions that never made it into research, but were amusing, instructive, or even useful in other ways. Playing the numbers helps. Third, luck, and the kindness, skill, and curiosity of friends and strangers, played a large role in the successes. It's difficult to explore new terrain without help. The most important conclusion, however, is that for me, and for others (scientists, engineers, artists, or citizens alike), curiosity uncovers endless unanswered questions, illuminates opportunities, gives a sense of parenthood to projects, and provides limitless amusement. It's fun. A utilitarian life may also be satisfying, but sharing some intellectual genes with a butterfly is not all bad.

Can curiosity be taught and/or learned? I would like to believe "yes," but my successes, both as teacher and student, are only so-so. We start life fueled by curiosity. All two-year-olds are incorrigibly curious: for them it's a skill necessary for survival. (They are also wonderful scientists. Imagine working out the basic elements of Newtonian physics, the structure of complex languages, and the elements of social interaction, entirely without benefit of differential equations or language, all in the first two years of life, and armed only with curiosity! How do they *do* that?) But then they begin to grow up. Albert Einstein famously said, "It is a miracle that curiosity survives formal education." (Although curiosity is certainly a characteristic of two-year-olds, it should not be *exclusively* a characteristic of two-year-olds!)

Scientists practice difficult professions, and are marinated in formal education more than most. Although technical skill is necessary, to teach students only the past of science does not teach them how to be curious about its present and future. (In partial compensation, students in science *are* taught to *notice*, and that skill leads in the right direction.) Fortunately, great teachers of music do not have to be great musicians, and some young musicians become great without great teachers. What applies to music probably also applies to other forms of art, including curiosity. Native aptitude helps, as does skilled instruction, but there is no set path to virtuosity.

That said, as both a geriatric student and a teacher with some decades of practice, I would suggest to younger colleagues:

- *Notice* the world around you. Everything you see hides secrets you do *not* understand. You have only to look. (And don't take my word for it: just reflect on the lives of Faraday, Darwin, and other truly great scientists.)
- Practice counterfactual thinking. If everyone agrees that proposition "X" is true, suppose, instead, that it is false.
- Go where there is no crowd. Counterpopulism works. It is politically, if not factually, correct, to assert that anyone can be a great scientist with enough effort. Whether true or not, it is almost certainly easier to be curious than to be hard working. So, separate your interests from those of others, and let your curiosity be your fanciful guide. If an area of research is already populated, curiosity will skip elsewhere, where there is more to discover.
- Save time to daydream. (My late colleague Jeremy Knowles used to say that the principal reason he went to seminars was to be slightly bored, and to allow his mind to wander.) Curiosity can drown in turbulent, fast-flowing reality.
- Look at *everything*, and consider questions you can ask but not answer as possible research programs. Humans were

always hunter-gatherers. Anything new might be interesting or edible (or uninteresting, or poisonous, but that's a separate kind of problem).

- Use curiosity to find bright, shiny objects, that is, genuinely fresh new ideas. Scientists relish them (especially if they can adopt them as their own).

Let us assume, for the sake of this essay, that curiosity, and "curiosity-driven research," are habits of mind that contribute to new ideas, and nourish creativity in science and elsewhere. Also consider that incuriosity might lead to a dulling of the senses, a bleaching of the colors of a marvelous world, and an indifference to the unfamiliar. Do our various communities in science encourage curiosity? The answer is clear: "No" and "Yes." If, particularly as a beginner, you write a research proposal using curiosity as its justification—"Here's a subject that my intuition tells me will be interesting, and if you give me some money, I'll figure out if there's something in it"—you (and it) will probably fail. Peer review is bureaucratic, and good at screening out bad ideas, unconventional ideas, and new ideas. If, instead, you propose solid developmental engineering of a well-established subject, get the money, and combine a sliver of it with curiosity to generate something *really* new, you will not be punished, and may ultimately even be rewarded. (If it is a new idea, you may, of course, still have trouble publishing it, but don't let that deter you.)

Because following curiosity can seem effortless, it is easy to assume it does not need to be learned, practiced, or encouraged, that it is not important, and that it will somehow take care of itself. But, as with many activities that are competing for time and attention in a utilitarian world, curiosity can atrophy from neglect. It can certainly be unfocused, and lead to nothing (or at least nothing immediately useful), but using it as the starting point for careful observation of nature and society is a nontrivial skill, and a starting point for new intellectual endeavors and adventures. It is one essential contributor to creativity in science, and a start in forcing new ideas into inflexible professional orthodoxies.

What happens to science without it? My students occasionally (for other reasons) ask "What is the one novel I *must* read?" I answer "1984."

That is a world without curiosity.

Or science.

Conflict of interest

The author declares no conflict of interest.

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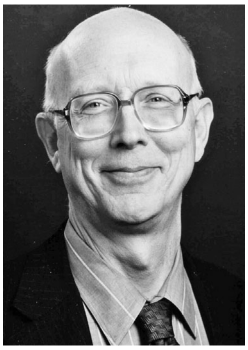
Essays



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