GROWING UP IN 'SCIENCE'

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Children are naturally inquisitive, and will poke bugs to see how they respond, toss twigs in a stream to see how far they will go before they get stuck, will take apart a toy to see what its pieces are like, wonder where the water disappears to when it goes down the drain. I grew up in a household in which exploration was not just tolerated but encouraged. Activities that I can remember began on the kitchen floor playing with pots and pans, removing all part that could be unscrewed. My father repaired everything—the roof, the radio, plumbing, electrical wiring, tuned the piano, repaired the car, as well as doing the vegetable gardening. As a child I watched him whenever he was doing such things, and he would explain what he thought was wrong and how whatever it was worked. My mother had an ancient Singer sewing machine, and inside its drawer she kept a small screwdriver for adjustments. I was allowed access to the screwdriver, as long as I put it back, and anything that could be assaulted with it was fair game. My mother described to me many years later a visit of the family doctor, who had come to the house to see one of my sisters. He remarked to horror with a stern voice that I had taken apart the phonograph (the old hand-windup kind) and the parts were scattered around the floor of the living room—in short, that I was not being adequately supervised and was misbehaving. Her unastonished reply was 'well, *if* he can't put it back together, his father will'. I still remember the shape of her screwdriver. The other interesting piece of household equipment was the large magnifying glass, useful to examine ants, or make the sun burn a hole in a piece of paper.

A little later, my mother encouraged chemistry in the kitchen. I was given a few test tubes, corks, and children's books describing activities such as how to make hydrogen from zinc (taken from the casing of an old battery) and strong vinegar, or how to shoot a cork across the room using vinegar and baking soda; describing the unusual multiple properties of sulfur as it was heated to melting and beyond, and how to grow single crystals of sugar and salts. The hydrogen was identified by a satisfying 'pop' when ignited with a match. The crystals never came out as gloriously as the pictures in the books; yet one could see the symmetric forms, and wonder about how they came to be. Invisible ink was another surprising feat easily done in the kitchen. While most students first see a color indicator of acidity in chemistry lab, my father showed me that red cabbage was a fine indicator dye, turning blue or red depending on the acidity of its surroundings.

Electrical things began by being given a couple batteries, some wire, and a few light bulbs. The activity I most remember from these is winding wire around a cluster of nails to make an electromagnet, and happily figuring out things to do with it such as making a telegraph to signal from my bedroom to the kitchen.

Tinker toys and an erector set with which to build followed. My ambitions were always too large for my clumsy fingers and the available parts, but how I wanted to build things that would 'work', that would do something interesting. Birthday gifts would include simple items like pulleys and rope, a saw, hammer and nails, chosen to help me explore the world of making things.

I wanted a radio. My parents did not want the noise that it would produce. The compromise was that I should build a crystal set, a radio receiver with no vacuum tubes (it was before transistors). I was given a set of ancient headphones and an old bulletin from the United States Department of Agriculture on building crystal sets. The entire parts list consisted of headphones, a crystal of galena (lead sulfide), and wire that you wound into coils on cardboard tubes. Such a set could receive radio stations as far as 75 km away, without the need for batteries. (The bulletin was written in 1930 to bring radio to farms that did not yet have electricity). Wanting something that received more distant stations, I found a design for a single vacuum tube radio, and saved money to buy the vacuum tube. My introduction to electronics was very 'hands on', building very simple things, making modifications, seeing what worked. And it was very inexpensive. The one real mystery in the crystal set was how a piece of wire making contact with a crystal of galena resulted in rectifying the radio signal to yield the audio sound. I did not understand that until I was a graduate student in physics 12 years later.

A bicycle presented new opportunities. Spokes would break, or the coaster brake would go out of adjustment, and I would take things apart. Rescue by my father, and perhaps a trip with him to the repair shop, would often follow. The trip to the repair shop was not to get a repair done—that was too expensive—but to find out how to do it and to buy necessary parts.

I took up building model airplanes from kits. The early ones were rubber-band powered. Later ones were powered with a small gasoline engine, from which I learned much of later use when I first had an unreliable automobile. I read a little about science in magazines, and an occasional book about astronomy or but more than anything else, devoured what I could find on how the useful inventions of the everyday world work.

Science at school was dreadfully taught. Before I was 12, there was no science at all. In beginning science, my teachers emphasized memorizing the names of things, not doing things, not understanding. My grades in these classes were terrible. I had two good science teachers. One was a biology teacher who emphasized *organizing* facts, not memorizing them, and seeing the relationships between living things. It was my first experience with science in the field, sciences of observation. The other was a high school chemistry teacher who treated teenagers as adults, taught by giving real lectures, and gave a laboratory in which I did experiments of sophistication that I could only eagerly read about when younger. Suddenly I was the best student in the class.

Physics is an exploration of what is not understood about the way things are, in search of essential principles, facts, and quantitative description. Some fall in love with the mysteries of the origin of the universe, or the nature of the world at distance scales that are unbelievably small. For me, having been brought up curious about the world around me, and fascinated to understand and manipulate it, the most interesting physics involves the properties of things at the human scale, and how these are related to underlying more microscopic structure and properties.

From this background, it is obvious that my university studies would ultimately lead to condensed matter physics. The first ten years of research was on the interaction of light with crystalline solids, and how this was related to the electronic structure of solids and the quantum aspects of light. It was a marvellous era, for there were places which yet lacked zero-order understanding. Experiments were coming along at a great rate so that theory was quickly tested. It was, in hindsight, also an excellent training ground for acquiring a wide vocabulary of mathematical models of general use.

As the understandings of solids grew, I turned toward biological systems, where zero-order explanations in physical terms were chiefly not yet known, and where quantitative experimental facts of the sort that physics is built on were slowly being accumulated. The nature of my contributions was unusual, for I tended to ask a different kind of question. Indeed, while I am now chiefly known for my contributions to theoretical biological physics, the nature of the most significant contributions has *not* been mathematically profound. I have managed only to identify simple problems, to state them clearly, and to describe their solution in a way that makes them understandable and amenable to a physics investigation.

My most cited paper is the first I ever wrote on how the brain works. It links a known physics topic—magnetism and the spin glass—to the psychological phenomenon of associative memory, by way of a physics-type abstraction of the behavior of a network of interconnected nerve cells. It introduced the idea of computation in neurobiology as being carried out by the dynamical trajectory of a system with many degrees of freedom moving toward a (temporary) fixed point of its dynamics. Known now as the 'Hopfield model', this insight led many physicists into neurobiology by illustrating how close the questions of neurobiology could be to questions in physics, and how useful a physics-type modeling approach could be in neurobiology. It took more than two years of attending meetings and seminars on neurobiology to enable me to find that problem. My most cited paper in molecular biology described 'kinetic proofreading' (a general method of 'proofreading' at the molecular level) and was also the first I wrote having anything at all to do with tRNA or protein synthesis. Again, it was a matter of posing the right question. A biologist would ask 'how does the desired reaction happen?' I found a new principle by asking instead 'why does the undesired reaction not take place, when it is so similar to the desired one?'

My present enthusiasm in science might be described as 'how do we think?' It is the type of question I have always pursued, though with age the questions have gotten harder. Is it biology or physics? It doesn't matter. Perhaps physics is best defined simply as 'what those trained in physics do'.