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Abstract. Craig Bohren has enhanced science education in many ways, including email mentoring of non-scientists and scientists, informal science books, and science textbooks. I had numerous interactions with Bohren over a ten year period, and he influenced my own informal-science-education efforts, which include educational modules, science education posters, and curriculum reviews.

Keywords: Informal science education, mentoring, science education, science posters, Craig Bohren.

1 INTRODUCTION

In his preface to *Fundamentals of Atmospheric Radiation* [1], Eugene Clothiaux observed that his co-author "Craig Bohren lives in a different world from the rest of us. During the course of writing this book, he has received hundreds, if not thousands, of emails from people with no real experience in science, or a bit of informal training, or plenty, or even experts in this field and that. To the best of my knowledge he has answered many, perhaps most if not all, of these emails as he tries to bring understanding to the people who write to him. My guess is that this diversity of his experience over many years has contributed to his strong and forceful statements in his discourse on science."

This article puts a personal touch on the above observation (including the strong and forceful statement part!), as I have been fortunate to have had scores of email conversations on science education topics with Bohren over the past 10 years. Based on my experiences with him, I would venture that he has indeed answered all of the emails he has received. In doing so, he has contributed a wealth of information to countless beneficiaries and made an impact on their knowledge of science. This is but one such example.

2 SCIENCE EDUCATION: INTERACTIONS AND IMPACT

In the summer of 1999, I took a family cruise to Alaska and noticed the amazing colors of the glacial ice, varying from clear to white to blue, and occasionally green. Noticing that the explanation for the color of ice disbursed by both the rangers and the visitor information posters at the Mendenhall glacier visitor center in Alaska was incorrect, I promised to send them a correct rendition. Although I was quite confident that I understood the reasons for the varying colors of glacial ice, I contacted Jeff Dozier of the Snow Hydrology Group at UC Santa Barbara for information about the optical properties of snow and ice. He suggested that I contact Craig Bohren, as someone with significant expertise in this area. I did, and that has led to a 10 year relationship of mentoring that has made a significant impact in my professional and educational life.

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2.1 The color of ice

My first email response from Craig was to be typical. I was someone he didn't know, and yet he wrote a treatise with the standard Bohren touches, sent to me the same day (August 25, 1999) that I sent him an email requesting information about the color of ice and snow. First, he cited the standard article on the color of water [2], provided a brief history of the study of the color of water and ice [3], and concluded with "The Belgian scientist, Walthere Spring, understood the colors of ice more than 100 years ago, but his work was buried in obscure Belgian scientific journals." Second, I got to experience his utter frustration at scientific nonsense, especially when propagated by prominent scientists. When discussing the confusion about the color of ice, he wrote, "the usual explanation is that the blue of ice is a consequence of 'Rayleigh scattering.' This rubbish we owe to Raman, and because of his prestige it has been propagated thoughtlessly by folks who should know better." The third aspect was the kind but firm manner in which he dealt with his emailers on a personal level. In response to my suggestion that the green color of icebergs might possibly be due to a multilayer interference effect, he wrote, "… to expect such a coherent structure in an iceberg would be like expecting a ton of bricks dropped from an airplane to form a house." His literary flair was endearing and unmistakable. So was his no-nonsense point.

After some additional consideration about this issue, I asked him to comment on my final explanation of this effect, namely that "Ice is white when the path length of the light in the ice is short due to the higher density of trapped air bubbles in the ice, which scatter the incident light out of the ice before much of the red end of the spectrum is absorbed. Ice is blue when the path length of the light in the ice is sufficiently long that a significant amount of the red part of the spectrum is absorbed. This probably corresponds to a lower density of trapped air bubbles in the ice" [4]. To which Bohren replied, "I completely agree. As far as I am concerned there is not a better or simpler explanation, especially one expressed in so few words." Based on this encouragement, I wrote up a short article about why ice is either blue or white and sent the article to the aforementioned park rangers. I also posted this article on the web [4]. Knowing that I had an incredibly competent and fun mentor, I decided that this available expertise was an opportunity to be cherished and utilized, but not abused.

2.2 Season's poster: Is atmospheric absorption a major cause of the seasons?

Student (mis)understanding of the reasons for the seasons has been a "poster child" for why standard physics instruction involving passive lectures is ineffective for student understanding of conceptually difficult subjects [5]. After researching this topic, I was unimpressed by existing relevant curricula and decided to develop a poster [6] that incorporated key aspects of both qualitative and quantitative reasons for why we have seasons. The simple numerical calculations and graphs that I developed, with feedback from Craig, strongly indicated that atmospheric absorption was not a contributing factor to why we have seasons, despite the prominence of this explanation on web sites and in textbooks [7].

This led to another flurry of email discussions with Craig. After some initial efforts on my part, Craig encouraged me with the following advice: "It occurred to me that you might consider submitting a brief manuscript to The Physics Teacher showing that atmospheric attenuation is not a major factor in seasonal temperature variations. All you have to do is compare the measured surface insolation with insolation at the top of the atmosphere. You've already done most of the work. One more curve would finish the job … Attenuation per se by the atmosphere is irrelevant. There is attenuation in summer and in winter. So the question is, is attenuation in winter sufficiently greater (possibly because of longer atmospheric path lengths) to be a major contributor to seasonal temperature variations (i.e., daily solar insolation)? What we want for a given location (latitude) or several locations is the ratio of winter to summer insolation at the surface to this same ratio at the top of the atmosphere. By winter could mean December 21 (in the northern hemisphere) and by summer could mean June 20. If these two ratios are almost the same to within, say, 10%, then we could say that atmospheric attenuation accounts for less than 10% of the variation between summer and winter. If one were to show curves, it perhaps ought to be these two ratios as a function of latitude for a range of latitudes (locations).” With this encouragement, I did generate a series of curves that seem to definitively show that differential atmospheric attenuation is not a contributor to the seasons [7]. Although this analysis has been presented at a few workshops to high school teachers and posted on the web [7], the paper to the Physics Teacher has yet to be written.

2.3 Correcting incorrect physics in classic textbooks: Why clouds are white

Craig and I agree that students should have a conceptual understanding of physics; this is certainly captured in his books and papers. After reading an incorrect explanation about why clouds sometimes appear white (“A cloud is composed of a variety of droplet sizes. The tiniest scatter blue, slightly larger scatter green, and still larger scatter reds… The overall result is a white cloud.”), and sometimes dark in the classic conceptual high school physics book, not surprisingly titled, *Conceptual Physics* [8] by Paul Hewitt, I emailed Craig and mentioned that he might want to correct the incorrect reason given. Craig immediately emailed Paul, with his characteristic honest opening of, “You are wrong. Sorry, but that’s the way it is… All particles scatter light of all frequencies, although they may not do so equally… Now suppose that that the particle is larger than the wavelength. Such a particle scatters essentially independent of frequency.” Plus another 4 pages of further explanation, including, “Your assertion about dark clouds resulting from absorption is also wrong, although you are not alone in making this error. Chapter 11 of *Clouds in a Glass of Beer* discusses dark clouds as does Chapter 18” [9]. This error was presumably removed in subsequent editions.

2.4 Ask a scientist column: Why are fog lights yellow?

As an occasional “expert” asked to answer questions for the Argonne National Laboratory NEWTON Ask a Scientist Column [10], one such question was, “Why are fog lights yellow? Does it help that they are?” I was not quite sure so I asked Craig if he knew the answer to this question and of course, he had much to say on this matter. So I deferred to his answer, which is now posted on line [11]. His response includes classic Bohrenisms: the plausible, common, but wrong explanation; a succinct version of the correct explanation, and some fascinating history. "First I'll give you the wrong explanation, which you can find here and there. It goes something like this. As everyone knows, scattering (by anything!) is always greater at the short wavelength end of the visible spectrum than at the long wavelength end. Lord Rayleigh showed this, didn't he? Thus to obtain the greatest penetration of light through fog, you should use the longest wavelength possible. Red is obviously unsuitable because it is used for stop lights. So you compromise and use yellow instead.”

“This explanation is flawed for more than one reason. Fog droplets are, on average, smaller than cloud droplets, but they still are huge compared with the wavelengths of visible light. Thus scattering of such light by fog is essentially wavelength independent. Unfortunately, many people learn (without caveats) Rayleigh's scattering law and then assume that it applies to everything. They did not learn that this law is limited to scatterers small compared with the wavelength and at wavelengths far from strong absorption… Designers of headlights have known for a long time that there is no magic color that gives great penetration. I have an article from the *Journal of Scientific Instruments* published in October 1938 (Vol. XV, pp. 317-322). The article is by J. H. Nelson and is entitled ‘Optics of headlights’. The penultimate section in this paper is on ‘fog lamps.’ Nelson notes that ‘there is almost complete agreement among designers of fog lamps, and this agreement is in most cases extended to the colour of the light to be used. Although there are still many lamps on the road using yellow light, it seems to be becoming recognized that there is no filter, which, when placed in front of a lamp, will improve the penetration power of that lamp.'"

2.5 Learning from his popular books, multiple scattering, the Doppler effect, and unexpected consequences

I first learned about multiple scattering by reading *Clouds in a Glass of Beer* [9]. The two chapters in this book, Multiple Scattering at the Breakfast Table and Multiple Scattering at the Beach, were a stimulating introduction to an area that is typically not covered in any physics or optics course. The only comparable (but inferior) conceptual resource that I have found is that developed by the DuPont Titanium Dioxide group that describes the physics of white paint [12]. The understanding that I gained mostly from reading *Clouds in a Glass of Beer* had unexpected consequences. I have often performed curriculum and science education program reviews on behalf of the National Science Foundation. For 3 years, I performed site visits for the Nanosense program [13], which was developed to introduce high school students to nanoscience. One of the curriculum modules developed was an investigation of Clear Sunscreen [14-15]. My understanding of this subject, greatly enhanced by those two chapters in *Clouds in a Glass of Beer* and many email discussions with Craig, allowed me to suggest improvements and correct some misconceptions about how sunscreens work, leading to what may be the only instructional material on multiple scattering developed specifically for the high school student.

Craig's writings also provided me with inspiration for my own education writings. When I read the chapter on The Doppler Effect in *What Light Through Yonder Window Breaks?* [16] , I was heartily amused by his description of the demonstration he performed for his students: "The classroom demonstration has been quite successful, perhaps as much for its scientific content as for the spectacle it presents of a middle-aged, sweating, red-faced professor who – so the students can hope – just might keel over from his exertions." But the conceptual way of understanding this effect was unique: using letters sent to a station from a moving train and examining the time difference between letter deliveries. In his characteristic honest fashion, Craig cited his inspiration from Gill's book, *The Doppler Effect* [17]. I was writing an education module at the time on The Physics of Safe Driving [18], and thought this would make an interesting mechanics problem, even though it had nothing to do with safe driving. So I adapted this idea to two motion problems that are now part of this education module [18].

2.6 Curriculum reviews: Interaction of light with carbon dioxide

I have been involved with numerous curriculum reviews at both the middle and high school level. During one review of a high school curriculum involving global warming, a question arose on to the details of how carbon dioxide contributes to atmospheric warming. Despite my efforts at finding a detailed and appropriate discussion of this problem, I was unable to find a satisfactory answer, so I posed this query to Craig. I asked, "When a carbon dioxide molecule absorbs an infrared photon, what happens next? Does it emit a photon with the same energy or possibly lower energy, or does it lose its energy by some radiationless/collision process?"

Craig then replied, "I think that it may be a mistake to concentrate on what happens to an individual molecule. Emission is determined by temperature, which in turn is a property of an ensemble of many molecules. But I know that there is a strong tendency for everyone, me included, to try to individualize processes even though this is inappropriate (maybe impossible)… Consider a gas of many molecules illuminated by IR radiation. Absorption of some of this radiation results in an increase in temperature of the gas… Some molecules that absorb IR photons must de-excite sometimes partly by non-radiative processes. If this were not true, it would be impossible to increase the temperature of a gas. I think you want to know what happens to an individual molecule, and I think that this is impossible to say. All we can determine is what happens to an ensemble of similar molecules." While not the single molecule answer I was looking for, it provided a new perspective, which I forwarded to the curriculum writers.

2.7 Inspiration and guidance for textbook writers

The preface to *Atmospheric Thermodynamics* [19] by Bohren and Albrecht should be required reading for all aspiring science textbook writers. Their stark admission is refreshing and unexpected. "We wrote this book inspired by the highly radical notion that textbooks ought to be rollicking good literature given that their intended readers are most young people, those through whom the juices of life flow strongest, and hence those most repelled by dry and lifeless textbook fodder." Many may "think that we have gone overboard in trying to stamp out misconceptions by frequent ridicule and by pointing out how they impede understanding." I certainly do not and have used this tactic in many of my education modules and workshops, particularly for the subject of primary colors and additive and subtractive color mixing [7]. Other textbooks should follow their lead and also be "guided by the accumulated wisdom in articles on thermodynamics and related topics published in the American Journal of Physics" and other relevant journals. The problems in this textbook, as well as in *Fundamentals of Atmospheric Radiation* [1] are also unique, relevant to everyday life, and highly thought provoking. They need to be seen to be believed. In the authors' words, "A question about thermodynamics asked by tattooed and bearded men wearing nose rings and riding chrome-plated Harley-Davidson motorcycles is by our reckoning a good question." [19]

After discussing how much I enjoyed reading his *Atmospheric Thermodynamics* book [19] and how amusing parts were, he responded, "Many scientists speak with grace and wit – about anything other than science. But as soon as they put on their lab coats they lapse into the dreadful prose they think is expected of them. Things were not always so. I sometimes read the old papers with tears in my eyes. Many of these papers were clearly written in the now forbidden first person and often expressed awe. Dull impersonal scientific writing is relatively new to science."

2.8 Philosophy of science

Craig's personal philosophy of science as well as his knowledge of the history of science are well worth noting. The most memorable of these philosophical statements include one from his view of the nature of science and one provided by a historical figure. In the preface to his book, *Clouds in a Glass of Beer* [9] he wrote, "Nowhere in it do I invoke the revelations of authorities to convince you of anything. In science there is no authority other than observation and experiment illuminated by reason. I urge readers to do their own experiments and make their own observations. Authorities do have legitimate uses, but not as weapons. The pronouncements of authorities should be weighed carefully – and then rejected if found wanting." And here is my favorite quip from Craig involving the wisdom of the ages: "Nature cannot be blamed for not arranging the universe so that it can be explained in sound bites. Alfonso X of Spain averred that 'had I been present at the creation, I would have given some useful hints for the better ordering of the universe.' I often feel this way. Life would be much easier for me (but also less interesting) if all of nature's complexities could be wished away, if all physical phenomena could be explained with one-liners."

3 FINAL THOUGHTS AND FINALLY MEETING

I first spoke to Craig and met him on the same day, March 19, 2009, nearly 10 years after our first email exchange regarding the color of ice. I also got to meet his lovely wife Nanette, “critic, copy editor, proofreader, photographer’s assistant, and model for racy photographs, she dreams that each book will be my last.” [16] While Nanette’s dreams will likely never be fulfilled, Craig certainly has fulfilled my dream of having a knowledgeable, erudite, and fun mentor to guide me through many educational challenges. And I am but one of many that Craig has touched throughout his career. I conclude with a salutation to Craig known by all who have communicated with him: Cheers!

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