Pioneers of Science Education

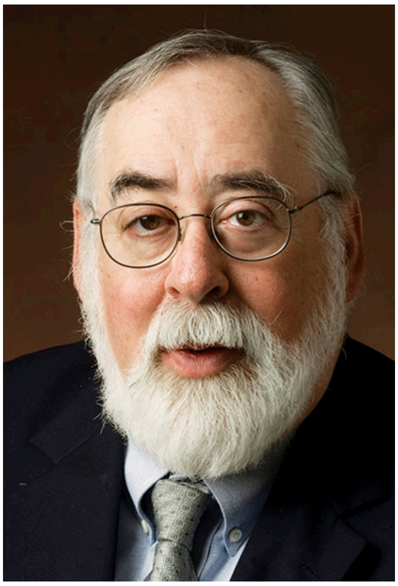
#16 George Bodner (1946-2021):

Late Emeritus Professor of Chemistry, Purdue University

'Unravelling curly arrow chemistry'

Dr Peter E. Childs

> In this series in *Science* we are looking at some of the important pioneers of science education in the last 200 years, and taken together the series provides an introduction to some of the important themes and key people in the development of science education. You can access back articles at www.cheminaction.com . I hope this will encourage to look further into the life and work of these pioneers of science education, and read some of their writings. Suggestions for people to include are always welcome.



George Bodner
1946 - 2021

I remember meeting George at a chemical education conference (10th ECRICE) in Krakow, Poland in 2010 and he was a larger-than life-character. He may not be well-known to Irish science teachers, unless you are interested in chemical education research or teaching organic chemistry. However, in the USA George was a colossus of STEM education, and published not only in chemical education but also in maths and engineering education. George M. Bodner, 75, died March 19th 2021 in West Lafayette, Indiana, after a long-term illness, and will be greatly missed by all who knew him. The ACS organised a Festschrift in his honour in August 2021, shortly after his death, (Introducing the Virtual Issue: George M. Bodner Festschrift - ACS Axial | ACS Publications), which collected articles relevant to George's CER interests.

Last year's BCCE had a memorial symposium: Celebrating the Life and Works of George M. Bodner, Purdue University, West Lafayette, Indiana 2022. This was very appropriate, as it was at George's home university where he built up a strong research group in chemical education over 40 years (Table 1). The topics covered indicate the breadth of George's research interests.

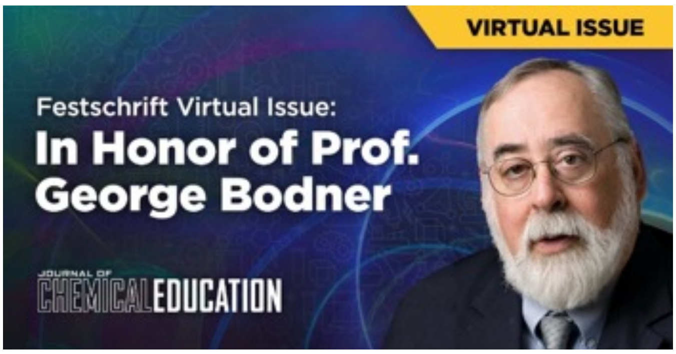


Table 1: In Memoriam: Celebrating the Life and Works of George M. Bodner (2022)
G. Bhattacharyya, A. C. Davis, Organizers, Presiding

11:00 Introductory Remarks. Session 1.
11:05 The relevance of George Bodner's to the work of modern practitioners. K. Casey, S. Holladay
11:25 In the Beginning was Problem Solving, Spatial Ability and a Motorcycle. J.R. Pribyl
11:45 Let's make learning more challenging: The influence of desirable difficulties on general chemistry students' problem-solving performance. O. Gulacar, B. Vernoy, A. Wu
2:00 Introductory Remarks. Session 2.
2:05 Lessons from George Bodner: "Framing" quality chemistry education research. M. Orgill
2:25 Theoretical Frameworks: How you Never Forget your "First Love". D.I. Del Carlo
2:45 Gadamer's Hermeneutics and Narrative Analysis: Complementary Theoretical Frameworks. J.W. Shane
3:45 Introductory Remarks. Session 3.
3:50 Revisiting the problem-solving mindset. D.E. Gardner
4:10 Toward an educational theory of "Organic Chemistry as a Second Language.". R. Ferguson, D.P. Cartrette
4:30 What does research on electron pushing tell us about students' sensemaking and the continued viability of the mechanistic approach to teaching organic chemistry?. G. Bhattacharyya

After Bodner's death, Purdue University published a Memoriam in 2021, including many testimonials.

https://www.chem.purdue.edu/media/news/2021/bodner_obit.

George Bodner at a conference in Krakow in 2010 with Liberato Cardellini (Photo: L. Cardellini)

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Education and career

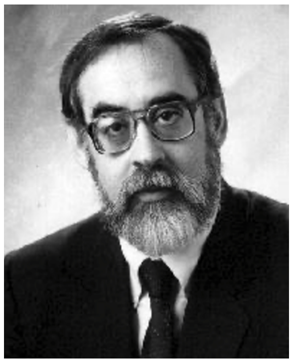
George was born March 8th 1946 in Rochester, New York. He received a BSc degree from SUNY Buffalo (1969) and obtained two PhD degrees, in Organic and Inorganic Chemistry, from Indiana University (1972). He had started as a history/philosophy major but switched to chemistry as he thought it was more fun and had better job prospects. This gave George a broad view of chemistry as a subject. Following his PhD he taught at the University of Illinois (1972-75), as a visiting assistant professor, and then at Stephen's College, Missouri, - a women's college in Columbia, MO - where he lasted for two years (1975-1977), teaching general, organic, inorganic, and biochemistry. George arrived at Purdue University in 1977, where he stayed until retirement in 2019. He was appointed to a faculty position in chemical education within the chemistry department, and I think this may have been the first such appointment in the USA. George was the Arthur E. Kelly Distinguished Professor of Chemistry, Education, & Engineering at Purdue and he was to put Purdue on the map as a centre for STEM education research. His work in chemical education research was done from within the Chemistry Department, thus making sure of a strong link between the subject and education. His graduate students went out to teach and do research in chemical education across the USA.

Table 2: Chronology of George Bodner's life

1946	Born Rochester, N.Y.
1972-75	University of Indiana, visiting professor
1975-1977	Stephen's College
1977	Joined Purdue University
1981	Division of Chemical Education set up at Purdue
2000	Arthur E. Kelly Distinguished Professor of Chemistry, Education & Engineering
2003	George C. Pimentel Award, American Chemical Society, (ACS)
2003	Nyholm Award, Royal Society of Chemistry (RSC)
2014	Helped found the American Association of Chemistry Teachers (AACT)
2018	Achievement in Research for the Teaching and Learning of Chemistry (ACS)
2019	Retired from Purdue
2021	Died Lafayette, Ind. Aged 75.

George's appointment at Purdue in chemical education led in 1981 to the setting up a Division of Chemical Education within the Chemistry Department, an important step, and a Chemistry Education Graduate programme. George made the case for locating chemical education within chemistry not in a faculty of education, because it promoted collaboration between chemists and chemical educators.

"the creation of a division of chemical education within a large, research-oriented chemistry department facilitated the growth of collaborative research on the teaching and learning of chemistry in advanced courses that requires both extensive graduate-level training within the content domain for the individual doing this work and access to practicing chemists from the content domain who are willing to collaborate on research of this nature." (Bodner 2010)



The young George Bodner

Professional awards

In 2003, Bodner received two awards: The ACS George C. Pimentel Award in Chemical Education (Bodner, 2003a) and the RSC Nyholm Medal in Chemical Education (Bodner, 2003b). George Bodner was given the American Chemical Society (ACS) Award for Achievement in Research for the Teaching and Learning of Chemistry at the ACS national meeting in New Orleans, in March 2018. This recognised his contributions to the development of discipline-based educational research on the teaching and learning of chemistry in both introductory and advanced-level courses. He is the only person (so far) who has won both ACS awards in chemical education, and the only one to receive both of these awards and the RSC Nyholm Medal. He received the highest honour Purdue confers onto a member of the faculty when he received the Morrill Award in 2013. This award recognizes Purdue faculty who best exhibit excellence in, and synergies among, all three dimensions of the professoriate – teaching, research, and service.

The Bodner Research Group at Purdue University, 2016 with Dr. Bodner and current/former Chemical Education students.

In his 2003 George Pimentel award address, he outlined the main components of a research thesis, based on 20 years as a supervisor and researcher. *"There is general agreement among individuals who teach graduate courses on educational research that a good Ph.D. dissertation proposal contains three fundamental components: A theoretical framework upon which the research will be built; a set of guiding research questions that are consistent with the theoretical framework, which the research will try to answer; and a methodology that is appropriate for probing the guiding research questions. This is the order in which these components might be described in the proposal, but it isn't the order in which the elements are generated. The first step toward a research proposal often involves the construction of a draft of the guiding research questions."* (Bodner, G., 2003a, p. 618)

Contributions to STEM education

Everyone who does research in almost every area does not do it alone; they rely on postgrad students and colleagues to collaborate in the work and George built up a very strong and effective research group at Purdue.

George's contributions to STEM education are almost too many to cover in a short article. He did research and published in maths education and engineering education, as well as in chemical education. This article will focus on his work in chemistry education research (CER). He most often published in these fields (George M. Bodner: H-index & Awards - Academic Profile | Research.com):

- Mathematics education (35.37%)
- Chemistry (25.00%)
- Science education (15.24%)

You can access some of his papers at the following links:

George M. Bodner - Publications (academictree.org)

(16) George M. Bodner (researchgate.net)

At Purdue he was responsible for introducing subject-focused education research, creating the graduate program in chemical education and later the School of Engineering Education at Purdue University.

He helped promote the Biennial Conference on Chemical Education, BCCE, which has become one of the most influential chemical education conferences, involved chemical educators at all levels. Over the years the emphasis on research has steadily increased, a mark of the influence of George and his former students.

He helped create the American Association of Chemistry Teachers (AACT) in 2014, which now has more than 4,000 members. He was heavily involved in the American Chemical Society at various levels, including the Board of Directors. After its creation he said this in a position statement. He was biased because he had promoted its formation to the ACS Board of Directors.

"From my biased perspective, the best news in recent years has been the commitment by the society to fund the creation of the American Association of Chemistry Teachers (AACT) and then the enthusiastic support of AACT by so many ACS members. As we noted when the creation of AACT was first proposed, the society used to do things to K–12 teachers, then for K–12 teachers; at long last, we are doing things with K–12 teachers. Nothing I have done since joining the society in 1969 has given me as much pleasure as being able to walk into the High School Day program at a national ACS meeting several years ago and tell the participants that the board had funded the creation of a new organization to be run by K–12 teachers of chemistry for K–12 teachers of chemistry."

He mentored 77 postgrad (grad) students, as well as many undergrads and faculty members. He was the author of more than 150 academic papers and wrote or contributed to many books (see below). He was a frequent speaker at national and international conferences. His contributions were recognised by a number of prestigious awards, both national and international. Purdue's Chemical Education program is the top-ranked program of its kind in the USA, and four of the 12 individuals to win the ACS Award for Achievement in Research for the Teaching and Learning of Chemistry have been Purdue faculty, which includes George. In addition, every member of the chemical education division who has spent 10 or more years at Purdue has won one of the two ACS national awards in chemical education. Quite an impressive track record.

You can get a feel for George's teaching in this 2016 lecture at a Physics Education conference: (78) PERC 2016 George Bodner Talk - YouTube

In the abstract for his talk George explains how he started in CER and how he switched emphasis from quantitative to qualitative research, which he decided would give better answers to the questions he wanted to answer.

"When I joined the faculty at Purdue, 40 years ago, I became interested in what has become known as discipline-based educational research (DBER). Having received my PhD in chemistry based on studies that used multinuclear FT NMR spectroscopy, it seemed obvious to me to start with quantitative methods based on traditional statistical techniques, which is what everyone seemed to be using at the time. But, as someone who taught medical students at UIUC before moving to Purdue, I soon concluded that all I could get out of statistical methods was evidence of a new "disease." It was never going to give me what I wanted, which was a "cure." I.e., a way to overcome some of the challenges of teaching and learning chemistry. So about 30 years ago, my group started to focus in qualitative techniques. It soon became apparent that much of our early work was not based on clear, concisely worded research questions. Nor did it build on a strong theoretical framework that would guide the way choices of methodology are made. (To be honest, neither did a lot of other DBER studies at the time!) Fortunately, I was surrounded by bright graduate students who were willing to help guide me in my search for a better way to approach such interesting questions as whether our model of what successful students' did when working on quantitative problems they encountered in the introductory chemistry course would have any resemblance to the model of successful problem solving both undergraduate and graduate students used when working on non-quantitative problems such as predicting the product of a chemical reaction or deducing the structure of a compound from FT NMR and FT IR spectra. My goal in this paper is to provide a glance at some of what we learned as a result of bringing qualitative research into the CER community. And to explain why we eventually published a book with the title: Theoretical Frameworks for Research in Chemistry/Science Education." (Bodner, 2016)

In 2010 George and Marcy Towns identified the eight areas of graduate research at Purdue over a period of 30 years: laboratory-based instruction, teachers' understanding, students' understanding, problem solving, alternative modes of instruction, computer-based instruction, research in advanced-level courses, and content-based research in other disciplines. (Bodner and Towns, 2010) Marcy Towns took over as the leader of Bodner's research group at Purdue. George's last papers appeared in 2020, including a review of biochemistry education. (Lang and Bodner, 2020)

Problem-solving

One of George's main interests was that of problem-solving, which was sparked by his realisation from his own teaching experience, that even bright students couldn't solve problems unless they were formulaic, algorithmic ones.

"During the course of that first semester [teaching general chemistry], I found that I enjoyed teaching and that the students enjoyed having me as their instructor. Everything was going well until I made the mistake of analyzing the students' answers to the exams I gave them. I was shocked; or, in the language of Jean Piaget, utterly disequilibrated. In spite of clear, concise, well-organized, and well-delivered lectures, I found that bright, hardworking science and engineering majors couldn't solve 'simple' problems on topics that had been taught and taught well! Thus, it shouldn't be surprising that one of the topics I became interested in as a beginning researcher in chemical education was problem solving." (Bodner, G., 2003b, p.37)

In this same paper Bodner describes what he calls the anarchistic model of problem-solving (see below Table 3).

Table 3: An Anarchistic Model of Problem Solving (Bodner, G., 2003b, p.41)

- *Read the problem*
- Now read the problem again
- Write down what you hope is the relevant information
- Draw a picture, make a list, or write an equation or formula to help you begin to understand the problem
- Try something
- Try something else
- See where this gets you
- Read the problem again
- Try something else
- See where this gets you
- Test intermediate results to see whether you are making any progress toward an answer
- Read the problem again
- When appropriate, strike your forehead and say, *'son of a ...'*
- *Write down 'an' answer (not necessarily 'the Answer')*
- *Test the answer to see if it makes sense*
- *Start over if you have to, celebrate if you don't*

George also summarised the research on problem-solving in his chapter in the 2015 book *Chemistry Education: Best Practices, Opportunities and Trends*. (Bodner, 2015) He and Dudley Herron explained why problem-solving is important for chemists.

"When the first author began work in chemical education, [George] became interested in research on problem solving for several reasons. First, problem solving is what chemists do, regardless of whether they work in the area of synthesis, spectroscopy, theory, analysis, or the characterization of compounds. Second, it was clear that individuals who were successful in chemistry courses either developed good problem-solving skills — more or less on their own —or brought these skills to their chemistry courses. Finally, it was obvious that we weren't doing as good a job as we could in helping less successful students learn how to build problem solving skills." (Bodner and Herron, 2002, p. 235)

He summarised his work on an effective model of problem-solving in 2017:

"For many years, the long-term goal of our research has been the creation of a model of the problem-solving process that has three characteristics:

It must be consistent with the results of our studies of how successful problem solvers complete problem-solving tasks.·

It must be teachable. It must be a model that can be given to students such that, if and when they use it, there is an improvement in their problem-solving skills.

It must be transferable. It must not only be applicable to more than one chemistry course, it must be relevant to courses for which chemistry is a prerequisite."

(Bodner *et al*, pp. 1419-1420)

Constructivism

George's most cited paper was the introduction he wrote to 'The Many forms of constructivism' in 2001, with two colleagues.

"Constructivist theories of knowledge are based on a fundamentally different assumption:

Knowledge is constructed in the mind of the learner . These nine words, by themselves, are unlikely to strike terror in the heart of anyone who "teaches" chemistry. In fact, the opposite is often the case — they strike a responsive chord for many who remember their own struggles to understand chemistry. It is only the implications of this phrase that cause trouble because this assumption leads one inexorably along the path to a corollary assumption:

Knowledge is seldom transferred intact from the mind of the teacher to the mind of the student. A second, more radical, form of the constructivist theory has been summarized as follows: Useful knowledge is never transferred intact." (Bodner et al, 2001, p. 1107)

Curly arrow chemistry: teaching about mechanisms in organic chemistry

One of George Bodner's main contributions was to understanding the problems beginners face in learning organic chemistry, especially mechanisms, based on his own experience in the classroom.

"In the late 1970s,when [George Bodner] joined the faculty at Purdue as an assistant professor in"chemical education"—whatever that was supposed to mean—[he] was hired to improve the teaching of the introductory, general chemistry course sequence.

Time and time again, our early work on the problems certain students had with organic chemistry provided evidence to support the following hypothesis: Although the formulas, equations and structures students write may look the same as what their professors write, there is a fundamental difference. The instructor writes symbols, which represent a physical reality. All too often, students write letters, lines and numbers that are not "symbols" because they have no physical meaning. They don't "symbolize" anything. (Bodner *et al*, p. 1415)

This was a continuing theme in his work, that even good students can learn off material without understanding it.

"The literature on conceptual problem solving has suggested that students can often produce correct answers to mathematical calculations in general chemistry courses without understanding the concepts on which their solutions are based. This study demonstrated that organic chemistry students can produce correct answers to mechanism tasks without having an understanding of the chemical concepts behind their responses. In both contexts we need to find a way to help good problem-solvers develop into good chemists. Within the context of organic mechanisms, this means helping the students recognize that there are concepts and principles that lie behind each step in the mechanisms they propose that need to be more clearly comprehended." (Bhattacharyya and Bodner, 2005)

Table 4: Summary of findings about student's use and understanding of mechanism in organic chemistry:

1.	The curved arrows held no physical meaning.
2.	They weren't symbols because they didn't symbolize anything in the students' minds.
3.	The students didn't understand the function of this formalism as it is used by practising chemists.
4.	Mechanisms were just blueprints for reactions they had to memorize.
5.	Mechanisms were not connected to activities in the lab.
6.	The most common justification for any step in the problem-solving process was: "It gets me to the product."

Chemistry teacher education

The American Association of Chemistry Teachers (AACT) was an initiative of the American Chemical Society (ACS), brought about in 2014 to serve as a professional community by and for K-12 chemistry teachers. AACT (teachchemistry.org) Its formation owed a great deal to Bodner's promotion and lobbying. He wrote about its creation in 2014. (Bodner, 2014) and it remains one of his most important legacies to chemistry teaching.

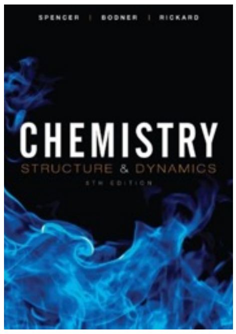
"As a metaphor for the sharing of PCK, let us consider the problems beginning chemistry teachers face through

the perspective provided by one of the students who came through the chemical education graduate program at Purdue. While reflecting on her experiences as a high school chemistry teacher, she noted that her roommate as an undergraduate had been a preservice elementary education major, and that the two of them shared an apartment after they graduated and took their first teaching positions. Our chemed graduate student noted that there was a fundamental difference between the experiences these two teachers encountered in the first few years in the classroom. When a problem came up in her roommate's elementary school classroom, she was able to reach into "a bag of tricks" she had developed during her preservice teaching program. Our chemed graduate student noted that she had a great deal of content knowledge as a result of the preservice teacher education program from which she graduated, but that her own "bag of tricks" for solving the routine problems that arose as a beginning teacher was virtually empty." (Bodner, 2014)

Important books

George Bodner either wrote, or contributed chapters to many books, including influential chemistry textbooks and laboratory manuals. Some are mentioned opposite.

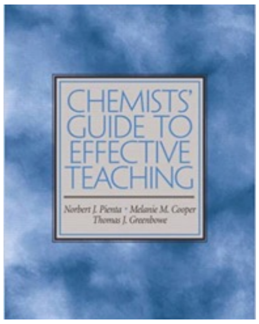
1. Chemistry textbooks.



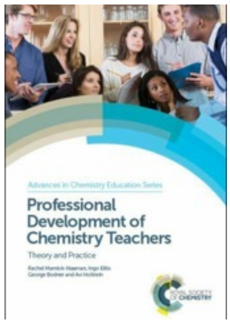
James N. Spencer, George M. Bodner, Lyman H. Rickard, 2011, Chemistry: Structure and Dynamics, 5th edition 2011

George M. Bodner and Harry L. Pardue, Chemistry: An Experimental Science ,5th edition, Wiley

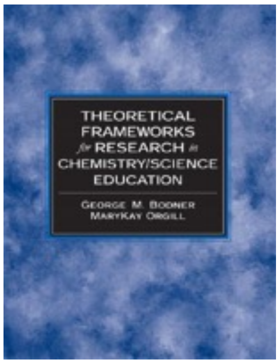
2. Books for teachers and researchers



Chapter 6 in Chemists' Guide to Effective Teaching, N. Pienta, M. Cooper, and T. Greenbowe, Ed., Prentice-Hall: Upper Saddle River, NY, 2005, pp. 67-76.



Mamlok-Naaman, R., Eilks, I., Bodner, G., and Hofstein, A., (2018), Professional Development of Chemistry Teachers, RSC



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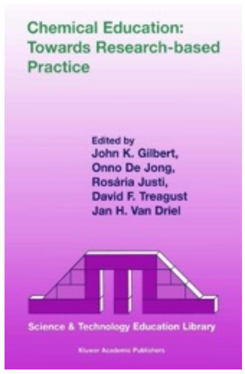

Bodner, G. M. and Herron, J. D., (2002), in Gilbert, J. K., De Jong, O., Justi, R., Treagust,D. F., and Van Driel, J. H. (Eds) Chemical Education: Research-based Practice, Dordecht: Kluwer Academic Publishers

George Bodner the person

A person's life is more than their work achievements or academic success. George left a significant legacy in his relationships with students and colleagues, as this extract from his obituary shows.

"But he will be remembered for more than his professional achievements. He was one of the most generous people with his time, resources, and spirit. He served as mentor to 77 graduate students as well as countless undergraduate students and fellow faculty members. Many of his friends called him a "Renaissance man" because of the breadth of his amazing intellect. In addition to being a world class scientist, his interests included history, philosophy, political science, literature, and music, and of course raising his pet dogs. Locally, he was a regular fixture at the Fiddler's Gathering and Friends of Bo events, and he was a long-standing member of his treasured book club. He also had the most beautiful heart. He genuinely cared about people and tried to help them reach their full potential. He often said that his greatest joy in life was to see his students become successful and contribute to the world. He always had time to help someone with a problem, or to just have a friendly chat. His kindness and charity knew no bounds. One of his greatest passions was social justice. And countless people have commented that they will remember his clever wit most of all."

In Memoriam: Emeritus Professor George Bodner - Purdue University Department of Chemistry

George Bodner, colleague, mentor and friend, is also reflected in these following appreciations. Thanks to the authors for sending them in.

Appreciations from colleagues

George Bodner was held in great esteem by his colleagues in America and worldwide. I asked some colleagues of George to give an appreciation of his work, and these are given below, including references.

1. If something goes wrong in the process of teaching/learning, the fault is not with the students but with the teacher

Georgios Tsaparlis

Professor Emeritus of Science Education, Department of Chemistry, University of Ioannina - Ioannina, Greece

gtseper@uoi.gr

George Bodner at the Royal Australian Chemical Institute 100th Annual Congress in Melbourne Australia 2017, with L to R Tina Overton, George, Dan Southam, Michael Seery.

George Michael Bodner was one of the great pioneers of chemistry education research. As most pioneers of the field, he started his research career as a pure/practicing chemist. He obtained a Ph.D. in inorganic and organic chemistry on the use of 13C FT NMR spectroscopy. He then worked for three years as a visiting professor at the University of Illinois at Urbana-Champaign, teaching general chemistry and carrying out research in pure chemistry. He was an enthusiastic and prolific teacher, and this explains why he soon turned his interest to chemistry education research.

Focusing on his performance as a teacher, I will invoke his own words from a foreword he wrote in a recent book on chemistry problem solving, which I edited: (1)

"Before each lecture in his general chemistry course at University of Illinois at Urbana-Champaign (UIUC) he [GMB] prepared an average of six pages of typewritten lecture notes ... He found that students responded well to his lectures in the end-of-the semester instructor evaluations and he felt that he had done a good job explaining the material such as, for example, the concept of molarity. But … to his surprise, no more than about 60% of the bright, hard-working science and engineering majors in the course were able to solve "simple" molarity problems, in spite of what seemed to have been well-crafted instruction. Something had gone wrong in the process of teaching/learning and he concluded that the fault was his, not his students'."

So for George: *"Teaching and learning are not synonymous; we can teach, and teach well, without having the students learn"*.(2) This experience led him to turn and focus his interest on chemistry education research. Meanwhile he had occupied a chair as the Arthur E. Kelly Distinguished Professor of Chemistry, Education and Engineering, Purdue University, USA. His experience from carrying out quantitative education studies led him to the conclusion that *"although studies based on traditional statistical analysis might tell them something about what was happening in a given content domain, it was not going to provide them with useful information about why this was happening, or what needed to be done".* (3) He then turned to qualitative research. (4)

He published many papers on various areas of chemistry education, e.g. organic chemistry, physical chemistry, and problem-solving in chemistry. At this point, I would like to add a few words about his contribution to research on problem-solving in chemistry, a field which he served for about four decades. (1) For George, ''problem solving is what chemists do, regardless of whether they work in the area of synthesis, spectroscopy, theory, analysis, or the characterization of compounds''. Fundamental has been his distinction between problems and exercises (3, 5, 6). Exercises can be solved by the application of algorithms, while a real/ novel/authentic problem is likely to require, for its solution, the contribution of a number of mental abilities, mainly of the so called "higher-order thinking skills". For his unique contributions to teaching and education research he gained many awards, e.g. the 2003 ACS George C. Pimentel Award in Chemical Education (4), the 2002-03 RSC Nyholm Prize for Education (6), and more recently the 2019 ACS Award for Achievement in Research on the Teaching the Learning of Chemistry.

With great sorrow I was informed of George's death soon before a book I edited was to be published by the Royal Society of Chemistry. The book is entitled *"Problems and Problem Solving in Chemistry Education"*, and includes a Foreword written by George. (1) Unfortunately, George did not live to see in print his thought-provoking autobiographical foreword, and indeed the whole book. All readers of the book will certainly enjoy it. I had collaborated with George in many ways since 2000, especially regarding the journal *Chemistry Education Research and Practice* (CERP), which I founded and edited for 11 years, during which time George provided valuable work as author, reviewer, and member of the editorial board. I met him many times in conferences and CERP editorial board meetings and I heard his eloquent lectures. George M. Bodner had a special, excellent and original spirit in his thinking and writings that impressed us all. He has been one of the top figures in chemistry education in the whole world, and the whole community will continue to benefit from his works and remember him forever.

References

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2. G. M. Bodner, 'Constructivism: A theory of knowledge', *J. Chem. Educ.,* 1986, 63 (10), 873–878.
3. G. M. Bodner, 'Research on problem solving in chemistry', in *Chemistry Education: Best Practices, Opportunities and Trends*, J. Garcia-Martinez and E. Serrano-Torregrosa (Eds.), pp. 181-201. Weinheim, Germany: Wiley-VCH Verlag, 2015.
4. G. M. Bodner, 'Twenty years of learning how to do research in chemical education', 2003 George C. Pimentel Award, *J. Chem. Educ.,* 2004, 81 (5), 618–628.
5. G.M. Bodner, 'Role of algorithms in teaching problem solving', *J. Chem. Educ.,* 1987, 64, 513–514.
6. G. M. Bodner, 'Problem solving: The difference between what we do and what we tell students to do', (Nyholm Award Lecture sponsored by the Royal Society of Chemistry), *Univ. Chem. Educ*., 2003, 7, 37–45

2. George Bodner: *Teaching and learning are not synonymous*

Professor Michael Seery

Visiting Professor, School of Health, Life and Chemical Sciences, Open University

Head of Digital Learning, Cardiff Metropolitan University

michael.seery@open.ac.uk

Professor George Bodner was the Arthur E. Kelly Distinguished Professor of Chemistry at Purdue University, Indiana, USA and was one of the great champions of chemistry education. His work spanned several decades, and early in his career he recognised that the practice of teaching deserved intellectual consideration. He set out his stall early in his much-cited 1986 paper explaining the principles of constructivism, (1) stating his hypothesis drawn from his observations as a teacher:

Teaching and learning are not synonymous; we can teach, and teach well, without having the students learn.

This interest led to an extensive research programme exploring a range of issues relating to student learning. The recent American Chemical Society *Festschrift* for Bodner named five major themes in his work:

(1) Constructivism as a lens for understanding student learning;

(2) Student conceptualization of organic chemistry;

(3) Understanding student approaches to problem solving;

(4) Visualization and spatial reasoning skills in chemistry education; and

(5) Conceptual understanding of chemistry.(2)

All of these drew on his interest in the student perspective – what were students experiencing, and what were they learning in that experience? I am particularly fond of his article – written with Trisha Anderson – that brought together many of the themes noted in the *Festschrift* entitled "*What can we do about 'Parker'? A case study of a good student who didn't 'get' organic chemistry*" published in the RSC's journal *Chemistry Education Research and Practice*. (3) Even looking at the title, Bodner's interest in placing the student at the centre of considerations about learning is clear. The research study explored how students approached the fast pace of teaching in an organic chemistry course, one which was considered to be taught well. The focus of sharing findings centred on the case of 'Parker', *"a bright, dedicated second year chemistry major"* and how their difficulties with the course materials are expressed. The careful work unearths layers of difficulties, such as difficulties in visualising the representations intended by molecular drawing, rather than the conceptual difficulties in understanding chemistry (that might be assumed from responses to assessment). Indeed 'Parker' was keen to know answers to '*why*' questions that often were not clear to them, often because the means by which the chemistry was being represented was not clear. It was a fascinating study because it threw up in great detail the lived experience of a student who wished to do well in their studies, with consequent implications for practice.

Bodner was a generous champion of others pursuing chemistry education research. I was lucky to meet him several times including at Purdue. My favourite memory is when he attended a seminar I gave at an Australian conference. He sat at the back of the lecture watching the presentation through a kind of mini-telescope, which while it was because of poor eyesight, I always thought of as a kind of metaphorical lens through which he viewed the relevance of chemistry education research for student learning.

Bodner died in March 2021, leaving an enormous legacy in his mentees (over 50 postgraduate research students), in his publications, and in his advocacy for the centrality of student learning in our considerations about teaching. In one of his final pieces of writing, he returns to that early advocacy of intellectual approaches to teaching, asking that we explore beyond *what* was happening in our teaching and learning, and instead – much like 'Parker' – ask "*why* this was happening". In this way, the teacher could then determine "what needed to be done to help students". (4)

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3. An appreciation of George Bodner

Brenda Capobianco

Professor Science Education, Purdue University, USA

Brenda Capobianco Faculty Profiles - Purdue University College of Education

bcapobia@purdue.edu

Professor George Bodner was an award-winning educator, chemist, and innovative scholar in science education. His contribution to the field were boundless. He published more than 150 papers, over 50 book chapters, laboratory manuals, and books, including a general chemistry textbook titled *Chemistry: An Experimental Science*, with colleague Harry Pardue. His 1986 paper in the *Journal of Chemical Education*, 'Constructivism: A Theory of Knowledge', is among the all-time most cited papers in chemistry education, approaching 2,000 citations. He was a master at bridging educational learning theories to scientific practices and establishing a long line of work on the role and impact of constructivism in the teaching and learning of chemistry.

While at Purdue University, he co-created the first chemical education graduate program and mentored over 75 graduate students. At the national level, Professor Bodner organized the American Chemical Society's formation of the American Association of Chemistry Teachers (AACT), where he convinced the ACS Board to fund the creation of a new organization run by K-12 teachers of chemistry for K-12 teachers of chemistry.

As a mentor and friend, he was incredibly generous with his time, intellect, and spirit. His love of history, music, and animals was contagious. He had the ability to make you feel at home through his glorious storytelling and humour. He genuinely cared about people and tried to help them reach their full potential.

(I met Brenda at the ISTA 2022 conference in Cork and when I found out she was a colleague of Georges I asked her to write me a short appreciation. Ed.)

Conclusion

It is hard to summarise George Bodner's contribution to chemical education, especially to chemical education research (CER) because they are so many in a variety of topics. Perhaps it is not too much to see George as the founding father of CER in the USA, making the Division of Chemical Education at Purdue University the premier centre for CER in the USA. He won all the major awards in chemical education and trained and mentored a generation of researchers, as well as teaching chemistry to thousands of undergraduates. He had a distinguished academic record and we can still read and apply the insights from his papers in our teaching, at both second and third level. George worked within a chemistry department and so he was concerned that discipline based education research (DBER) should be applied to teaching and learning at third level, not just at primary or secondary levels. George helped to make CER respectable within both chemical and educational circles, and to make scholarship in teaching and learning valued and recognised. All the memorials, testimonials and obituaries make the point that he was not only a good scholar and academic, but also a nice man, who cared about his students. Research was not just about 'publish or perish' but about improving the way chemistry is taught. It was fitting that when the BCCE conference came to Purdue in 2022 that there should feature a special symposium: In Memoriam: Celebrating the Life and Works of George M. Bodner (Table 1).

With his feet firmly under the table in the chemistry department, and with connections to maths, engineering and other disciples, Bodner always believed that the purpose of discipline-based educational research was to improve teaching and learning of subjects. This philosophy was articulated in a recent paper in 2017.

"Scholarship Reconsidered: Priorities of the Professoriate, Boyer advocated expanding the definition of the term scholarship by arguing that 'The most important obligation now confronting the nation's colleges and universities is to breakout of the tired old teaching versus research debate and define, in more creative ways, what it means to be a scholar.'

One step along the path toward this goal might involve recognizing the value of discipline-based educational research, which focuses on ways to overcome the challenges of teaching and learning in one particular content domain, such as organic chemistry. In much the same way that the goal of medical research is to improve the practice of medicine, ***the primary goal of chemical education research (CER)is to improve the way chemistry is taught."*** (my emphasis) (Bodner *et al*, 2017)

"So what is the take-home message we want to convey to others who might read this paper? It is quite simple: There is a fundamental difference between what we thought we had taught and what students learn. The research we have done over the course of more than 30 year shas demonstrated a clear difference between instructors and their students in terms of the meaning of many of the ideas, concepts and principles we teach. In particular, there is a clear disconnect between things we assume students have mastered and what they have actually learned. Not

because of anything they do or do not do, but because of the inherent nature of the learning process." (Bodner *et al*, 2017, p.1420)

There is certainly plenty for you to chew on and digest in George Bodner's work to improve the teaching and learning of chemistry.

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About the Author

Dr Peter E. Childs Emeritus Senior Lecturer, Dept Of Chemical Sciences, University of Limerick, Limerick, Ireland. peter.childs@ul.ie