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Introductory Retrospective

R. Byron Bird: The Integration of Transport Phenomena into Chemical Engineering

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This article, as is this issue of the AIChE Journal*, is a tribute to R. Byron Bird, who has had a profound impact on the discipline of chemical engineering, playing a dominant role in the chemical engineering science paradigm shift that occurred around 1960. His textbook,* Transport Phenomena*, with Warren Stewart and Edwin Lightfoot, fundamentally changed the way chemical engineers are taught fluid mechanics, heat transfer, and mass transfer. By showing the interconnections among molecular, microscopic, and macroscopic treatments of these three transport processes, as well as the underlying similarities among the three transport processes, he has enabled chemical engineers to contribute to many new areas. In his research he has focused on polymeric fluids – their rheology and fluid mechanics – again spanning molecular to macroscopic problems. Bird is also known throughout the profession as a superb teacher and lecturer. He is gifted in languages and music, and he has a great love of the outdoors. In this article, I try to highlight some of Bird's history and accomplishments in these many areas. His influence is clear in the papers that follow.*

Keywords: transport phenomena, Bird, polymer rheology, chemical engineering education, chemical engineering science, fluid mechanics, heat transfer, mass transfer

Introduction

Probably the defining characteristic of the engineering science paradigm shift in chemical engineering was the publication of the seminal textbook, *Transport Phenomena*, by Bird et al., in 1960.[1] This approach to core chemical engineering was particularly important for its unifying treatment of fluid mechanics, heat transfer, and mass transfer. This has remained a hallmark of chemical engineering education ever since. The early foundations for this book were laid in the monograph, *Molecular Theory of Gases and Liquids*[2] that Bird wrote with Hirschfelder and Curtiss in 1954. The second edition of *Transport Phenomena*[3] makes the connection between the two books clearer in explicitly showing the molecular origins of the transport laws for all three quantities—momentum, energy, and mass. The theme of connecting underlying molecular phenomena to transport laws and ultimately to macroscopic behavior was a central research interest of Bird and was developed extensively in his work on the rheology and fluid mechanics of complex liquids, particularly polymers. Much of this research work is captured in the two editions of the two volume text on the *Dynamics of Polymeric Liquids*.[4,5]

Bird is an exceptional teacher, expositor, and educator. Part of the success of *Transport Phenomena* in reshaping chemical engineering is clearly a result of his ability to distill the essence of a complex idea and to explain it clearly to a student, in the classroom or in a text. Throughout his books he makes beautiful use of parallels and common themes to capture central ideas as generalizations. At the same time, he routinely reduces the generalizations to practice in specific examples to show how these ideas are applied in specific areas of chemical engineering.

Finally, Bird has pioneered the area of macromolecular hydrodynamics as an intellectually interesting and industrially important field of research in chemical engineering (and mechanical engineering, physics, and chemistry). He was a key figure in building the Rheology Research Center at the University of Wisconsin (Figure 1), which brought together the disciplines of chemical engineering, mechanical engineering, engineering mechanics, and chemistry on the Madison campus, and was a "must-visit" destination for rheology scholars around the world throughout Bird's research career.

An Overview of Bird's Career

In 2010,[6] Bird published an article describing his career trajectory from early undergraduate school and onward. It is hard to improve on his own self-description, and I summarize some of his article in the following. Bird was born on February 5, 1924 in Bryan, Texas, where his father, Byron Bird was a professor of civil engineering at Texas A&M University.

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Figure 1. R. B. Bird around 1995.

University of Wisconsin - Madison photo.

Bird's undergraduate education in chemical engineering was split by WWII. He began at the University of Maryland where he did his freshman and sophomore years between the fall of 1941 and December of 1942. He then enlisted in the U.S. Army, serving until his discharge in April of 1946. Following basic training (with a number of students from MIT, including Alan Michaels and David Himmelblau, later professors at MIT and the University of Texas at Austin, respectively) a semester back at the University of Maryland, and then Officer Candidate School, Bird was assigned to the 90th Chemical Mortar Battalion, which was deployed for action in the Belgium-German-Austria area. In 1985, while we were attending the Fourth International Workshop on Numerical Methods in Non-Newtonian Flow in Spa, Belgium, I had a chance to visit one of the fields in which his unit engaged in battle. Although they are mostly gone now, Bob has stayed in close contact with his battalion since the war. A sad side-effect of assignment to an artillery unit has been hearing loss of all of the members as they got older. Bird returned to finish his undergraduate studies at the University of Illinois rather than at Maryland in the fall of 1946; he graduated with a BS in Chemical Engineering in 1947.

Following graduation from Illinois, Bird decided to attend the University of Wisconsin to work with Joe Hirschfelder in the Chemistry Department. I am not sure whether a contact allergy he developed in an organic chemistry laboratory at the University of Illinois was a factor, but from graduate school on, Bird focused his considerable talents primarily on theory. One of his thesis projects involved using the Chapman-Enskog theory with a Lennard-Jones 6–12 potential to compute transport properties of dilute gases and mixtures.[7] I believe this marked the beginning of his research in transport processes.

After graduate school, Bird spent a postdoctoral year in the Netherlands working with Professor Jan de Boer at the University of Amsterdam. This was the first of many trips abroad, particularly in the Netherlands and Japan, which had a profound impact on his career. These trips gave an outlet for his love of languages; in addition they led to many productive research collaborations. He tells the story[6] of learning from de Boer how he prepared for lectures not only by outlining the theoretical developments he would describe to the class, but also how he laid out in advance where on the blackboard he would place the material so that it would be easiest for the students to follow. Certainly Bird was a master at the blackboard! Following this postdoctoral year, Bird spent a year on the chemistry faculty at Cornell University before moving back to Madison.

Between Cornell and the University of Wisconsin, Bird worked at the DuPont Engineering Experiment Station in Wilmington, DE. During this summer of 1953, he had his first introduction to polymer rheology and decided that it offered many challenging problems for research. Apparently this impression stuck with him for the rest of his career. I find it interesting that he was told by his supervisor at DuPont, Henry Linton, that he was going to be a rheologist; Linton was an MIT graduate, who Bird had met in OCS during the war. While at DuPont Bird worked on the problem of understanding viscous heating in polymer extrusion.[8] His previous work in developing the basic equations of change from a molecular standpoint made him aware of the inclusion of a term accounting for viscous heating in the energy equation. His realization that most (chemical) engineers were not taught the basic mathematical formulation underlying heat, mass, and momentum transfer so important to industrial processes and that this omission made it difficult for engineers to tackle new problems like viscous heating had a strong influence on his desire to develop and teach transport phenomena to chemical engineering students.

Transport Phenomena

At the centennial meeting of the AIChE in November of 2008, Bird gave a talk[9] on the historical development of transport phenomena in the period up to and just after the publication of *Transport Phenomena* in 1960. Before the 1950s there were no integrated transport courses in undergraduate curricula in the U.S. At that time the dominant unit operations textbooks in use were those by Walker et al.[10] and by Badger and McCabe.[11] By this time, certainly both the continuum and molecular foundations of transport phenomena had been laid down. Continuum descriptions of the momentum flux, energy flux, and mass flux were all in place by the mid-1800s; these are associated with the names of Newton, Fourier, and Fick, respectively. Unified treatments of momentum, energy, and mass transfer had been developed in the kinetic theory of gases; these were summarized by Chapman and Cowling in 1939.[12] In 1950, Joe Hirschfelder and Chuck Curtiss, both in the Chemistry Department at the University of Wisconsin, taught a graduate course on transport phenomena in the Chemical Engineering Department at Wisconsin at the request of Olaf Hougen. According to Bird,[9] this subject covered much of the material that later appeared in Chapter 11 of "*Molecular Theory of Gases and Liquids*."

The mid-1950s was an important period for nucleating the development of transport phenomena at Wisconsin. Both Bird and Lightfoot joined the Department of Chemical Engineering at the University of Wisconsin in 1953, Bird coming from a year of teaching chemistry at Cornell University via DuPont and Lightfoot coming from Pfizer. Stewart joined the department 3 years later. Although Bird was originally slated by Hougen to teach thermodynamics at Wisconsin, he was drafted at the last minute to teach fluid mechanics, diffusion and mass transfer, and applied mathematics when Bob Marshall became Associate Dean of Engineering at

Table 1. Bird's Early Proposal for an Integrated, One-Semester Course on Transport Phenomena[6]

	MOMENTUM	ENERGY	MASS
Molecular	Viscosity	Thermal conductivity	Diffusivity
Microscopic	Equation of motion	Equation of energy	Equation of species diffusion
Macroscopic	Macroscopic momentum balance and macroscopic mechanical energy balance	Macroscopic energy balance	Macroscopic species mass balances

Wisconsin. During the preparation and teaching of the graduate fluid mechanics course in the fall of 1953, Bird became interested in showing the connection between the equations of change and the macroscopic balances, particularly the derivation of the mechanical energy balance. He published this in *Chemical Engineering Science* in 1957.[13] In the spring semester of 1954 he taught "Diffusional Operations." Preparation for this course led to a review article in *Advances in Chemical Engineering*.[14] The approaches developed in these two subjects and summarized in the corresponding publications captured important aspects of the organization that characterized *Transport Phenomena*, namely teaching in one subject an integrated view of the transport of the three physical quantities— momentum, energy, and mass —at three different scales—molecular, microscopic (continuum), and macroscopic. This is illustrated in Table 1, which Bird used in describing his idea for a transport phenomena subject at a meeting of deans of engineering at Purdue in 1957.[15]

Substantially expanded versions of this table appear in the preface to the first edition of *Transport Phenomena* and in Chapter 0 of the second edition, where they are used to explain the organization of the book.

It is interesting that at the University of Wisconsin a course in transport phenomena was originally considered in the Nuclear Engineering Department rather than in Chemical Engineering. It was a challenge by the Physical Sciences Divisional Committee, the university committee responsible for approving the proposal developed by Bird for this course, to the Dept. of Chemical Engineering that lead to the department's approving transport phenomena in chemical engineering for the fall of 1957. Bird, Stewart, and Lightfoot all volunteered to develop this new subject and wrote early drafts over the summer.

Bird is a prolific writer, and he managed to write drafts of Chapters 1–12 during the first half of August of 1957. The remaining 10 chapters were developed in "real-time" during the fall semester along with developing examples, problems, figures, etc. These drafts with revisions, new examples, and problems were published as *Notes on Transport Phenomena*[16] by Wiley as a limited edition in 1958. This limited edition was tested at the University of Oklahoma, Northwestern University, Johns Hopkins University, and Illinois Institute of Technology. The feedback from these institutions and from experience at Wisconsin led to a complete rewriting of the book, and the first edition of *Transport Phenomena* was published in 1960.

As a testimony to *Transport Phenomena*'s impact and staying power, the first edition went through 62 printings (see Figure 2 [17]). The second edition appeared in 2002, with a revised second edition in 2007. Students who were fortunate to take this course from Bird were treated to intermediate "editions" by means of the numerous "page inserts" that Bird created to clarify text and introduce new material and examples. My early copy of *Transport Phenomena* is literally bursting at the seams because of all the page inserts!

I was an undergraduate in the late 1960s at Georgia Tech and studied fluid mechanics, heat transfer, and mass transfer out of both McCabe and Smith's *Unit Operations* and from *Transport Phenomena*. The contrasting approaches certainly had a profound impact on both my choice of graduate school (Wisconsin) and career path. I am sure that it has had similar impact on countless other engineers and scientists.

Rheology and non-Newtonian Fluid Mechanics

In the late 1960s, after finishing a four-year stint as department chair, Bird decided to focus his research efforts on molecular understanding of the rheology of polymeric liquids and of their fluid dynamics. This he began with a one-month trip to Japan, meeting with scientists there to learn about molecular theories of polymers. He then spent a month on Waikiki Beach in Hawaii digesting reprints of seminal articles in this field and thinking about the problems he would tackle in his research program in the ensuing years. This turned out to be a very productive month for Bird.

On returning to Wisconsin one of his early research projects was a review article[18] summarizing and extending the work on use of dumbbells models in the kinetic theory of polymeric liquids. As the authors point out, although the dumbbell models are very simple mechanical models of polymers, they are very useful for teaching kinetic theory of polymers and its connection to macroscopic flow properties; they also provide very simple models for exploring the consequences of different kinds of intramolecular forces (the

Figure 2. Bird, Stewart, and Lightfoot with special leather-bound copies of the final printing (62nd) of the first edition of Transport Phenomena.

It was in print for 41 years.[17] [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 3. Ole Hassager, Bob Bird, and Bob Armstrong at the Society of Rheology Annual Meeting in October 2006.

Missing from the Dynamics of Polymeric Liquids authors is Chuck Curtiss (Volume 2). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

connectors) on rheological properties. This material was also used in teaching Chemical Engineering 725 at Wisconsin, "Structural Theories of Fluid Dynamics." There always seems to be a strong connection between research and education in Bird's work.

At about the same time, Bird began teaching a course in polymer fluid mechanics, Chemical Engineering 525 "Macromolecular Hydrodynamics". For this he prepared a hand-printed "booklet" of about 100 pages describing continuum theories of polymer rheology and their application to solve fluid mechanics problems. I started graduate school at Wisconsin in the fall of 1970 and, therefore, had the great opportunity to have my first exposure to both the continuum and molecular descriptions of polymer rheology from these (and other) subjects at Wisconsin.

Ole Hassager, who was a fellow graduate student with Bird at the time, and I had taken these courses together and both felt that there would be tremendous value to others beginning in the field of polymer rheology to have a book that captured and expanded this material. Just before we graduated in May of 1973, we jointly approached Bird with the idea of a book on Macromolecular Hydrodynamics. I believe he thought we were nuts, but agreed, so we began in earnest that summer outlining chapters and assignments and getting the first few chapters drafted. Over the ensuing academic year, Bob and Ole, who stayed on for a year as a postdoc, developed new material for the book, including (along with Said Abdel-Khalik) an improved understanding and development of corotational frames of reference to derive nonlinear rheological continuum and molecular models[19] while I began my career at MIT and used the opportunity to work on my parts and to test an early version of "Macromolecular Hydrodynamics" on MIT students.

We spent the summer of 1974 together in Madison, sequestered in the corner classroom on the third floor of the Chemical Engineering Department. We each had an IBM Selectric typewriter and a goal of producing 10 pages of typewritten text per day for distribution to the others. It was a wonderful experience with lots of debates and hikes, and by the end of the summer we had most of the book drafted. We were ultimately encouraged by the publisher, Wiley, to split the book into two volumes, because it had gotten too long. We decided on a split into volumes on continuum and molecular topics; and because of the profound influence Chuck Curtiss had had on our thinking on kinetic theory, he was brought on as a co-author on the second volume (Figure 3).

The first edition appeared in 1977 as *Dynamics of Polymeric Liquids, Vol. 1: Fluid Mechanics*[4] and *Vol. 2: Kinetic Theory*.[5] The first edition made great use of the corotational approach for obtaining objective constitutive equations, which we felt provided a much simpler way of explaining and utilizing the idea of objectivity (or material frame indifference) than the codeformational approach that was most common at the time, but which seemed to require use of general tensor analysis. In 1987 we published a substantially revised second edition, which among other major changes switched from the corotational approach to codeformational one, which we had figured out how to do without general tensor analysis, shifted emphasis from rheology to fluid mechanics, and included a lot of the new phase-space kinetic theory for polymers that Bird and Curtiss had developed. *Dynamics of Polymer Liquids* has been widely cited in the field. In 1988 the first edition was named a citation classic.[20]

Languages, Music, and the Great Outdoors

Bird is an extraordinarily gifted individual with many interests and talents beyond science and engineering. These include a love of languages, music, and the great outdoors.

Bird's love of languages dates back to his exposure to his mother and father's foreign language books as he was growing up. Indeed, he had planned to major in languages in college until his father, a successful civil engineer, nixed the idea. By my count, he has some fluency in speaking and/or reading and writing in eight different languages. The two that he has focused on particularly are Dutch and Japanese; these can be traced to extensive travel in the Netherlands and in Japan. Bird has also taken great advantage of the international character of a large university like the University of Wisconsin, engaging foreign students and visitors and faculty from other countries in practicing their native language whenever possible.

He has authored a number of books in foreign languages. In 1958, when Bird returned from Delft, he met and began collaboration with William Shetter in the German Department at UW. This led to publication of a Dutch reader,[21] which went through two editions, and a later literary reader.[22] With Professor Edward Daub, who in 1976 was the founding director of the first program in technical Japanese translation in the U.S., and Professor Nobuo Inoue at the Science University of Tokyo, Bird produced two books to help students learn to read technical Japanese.[23,24] With Sigmund Floyd, a former graduate student in the Chemical Engineering Department, he wrote a supplement to *Basic Technical Japanese* on polymer science and engineering.[25] Four years ago in 2009 he wrote a book on the usage of numbers in Japanese.[26]

Bird's gift of languages is probably coupled with his love of and gift for music. His particular interest has been the organ and piano. He has taken advantage of his extensive international travel to play organs in many famous churches, cathedrals, and concert halls.

I did not know, until I stayed at his apartment during one of my book-writing trips to Madison, that Bob also composes music. While writing this article, I dug out from the

Figure 4. Canoe trip to Quetico Provincial Park in 1992 with Bob Bird, John Wiest, David Armstrong, and Bob Armstrong.

John Wiest took the photo and is not shown. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 2. Ph.D Students of R. B. Bird

Name	Year of Ph.D.
Longmire, David R.	1957
Griffith, Richard M.	1958
Fredrickson, Arnold G.	1959
Slattery, John C.	1959
Hsu, Hsien-Wen	1959
Brock, James R.	1960
Ziegenhagen, Allyn J.	1962
McEachern, Donald W.	1963
Sadowski, Thomas J.	1963
Meter, Donald M.	1964
Williams, Michael C.	1964
Sutterby, John L.	1964
Turian, Raffi M.	1964
Huppler, John D.	1965
Spriggs, Thomas W.	1966
Ashare, Edward	1968
MacDonald, Ian F.	1968
Carreau, Pierre J.	1968
Hill, Christopher T.	1969
Wang, Chien-Bang	1969
Harris, Everette K.	1970
Stevenson, James F.	1970
Warner, Harold R. Jr.	1971
Armstrong, Robert C.	1973
Hassager, Ole	1973
Grimm, Roger J.	1977
Riddle, Michael J.	1977
Gottlieb, Moshe	1978
Prud'homme, Robert K.	1978
Co, Alberto ("Albert")	1979
Graham, Alan L.	1980
Christiansen, Richard L.	1980
Johnson, Norman L.	1983
Dotson, Paul J.	1984
Saab, Hassane H.	1984
Yarusso, Barbara J.	1985
Wiest, John M.	1986
Burdette, Steven R.	1987
Liu, Tony W.	1989
Schieber, Jay D.	1989

piano bench in our living room several scores that he wrote, including "A Variation on 'Wilt Heden Nu Treden,'" "Sunset Reflections on Buckingham Lake," and "A Quiet Stretch on the Cache River." He has also composed numerous fugues. A reflection on his playful approach to composition (and other work) is the "Chaconne on Two Cabbages," which he wrote in 2000. According to the note that he wrote at the end of this piece: "The CHACONNE is traditionally in $^{3}/_{4}$ time and in a minor key (here E-minor). The theme, stated initially in the bass, should be no longer than eight measures. The theme is then repeated in the bass in a succession of "variations" (here twelve). For the sake of variety, the theme can be transferred to another voice (in variation #4, the theme is in the soprano, in #5 in the tenor, and in #6 it is in both voices, but staggered). The variations are generally quiet at the beginning and increase in complexity as the chaconne progresses. The theme here consists of the notes CABBAGE-CABBAGE, just for fun." One of the fugues he wrote is a based on the theme from "Three Blind Mice."

Bob developed a love of wilderness canoeing while a graduate student at Wisconsin. He tells the interesting story of skipping studying for his prelims in chemistry to take a two-week canoe trip. He ended up failing the prelims and having to take extra subjects. I do not recall him ever mentioning this until his 2010 article in *Annual Reviews of Chemical and Biomolecular Engineering*; it certainly did not dampen his enthusiasm for the great outdoors. A de facto requirement for a Ph.D. with Bird is taking a two-week wilderness canoe trip; he has done 75 of these over his career. I confess that I somehow managed to defer this requirement for almost 20 years, when I went on a two-week canoe trip with Bob, John Wiest, and my oldest son, David, in Quetico Provincial Park in northern Ontario Province (see Figure 4). I have to confess that Bob is right that wilderness canoeing is an unparalleled way to decompress (or "let your eyeballs get spherical again" as Bob sometimes says), and also that I have not been on a canoe trip since! Probably his most ambitious canoeing adventure was a three-week trip down the Coppermine River. He and a group of seven others, including a number of faculty members from the medical school at UW, were air lifted onto a lake that marks the source of the Coppermine. From there they canoed north to the mouth of the river on the Arctic Ocean at a town called Yellowknife. One of the members of the group filmed the trip, and Bob used to give lectures on the trip along with the movie. The mosquitoes were enormous and ubiquitous, and the final week of the trip was in a canyon. Their party was the fourth group ever to canoe the entire Coppermine.

Figure 5. Bird receiving the National Medal of Science from President Ronald Reagan in the Rose Garden at the White House, June 25, 1987.

In addition to canoeing, Bob used to take graduate students on hikes. He would teach an early morning (7:45 AM) graduate class on Tuesday, Thursday, and Saturday (yes, back in the days of Saturday classes) so that after class, there was time for a hike around Governor Dodge State Park or Devil's Lake. Many distinguished visitors to the Rheology Research Center at Wisconsin would take part in these outings. It was a great way to get to know leaders in the field on an informal basis.

Honors and Awards

Bird has been widely recognized for his profound contributions to chemical engineering research and education and to science more broadly. The awards began in 1959 with the Curtiss-McGraw Research Award from the American Society for Engineering Education. In his field of research specialization, rheology, he was recognized by the Society of Rheology with the Bingham Medal in 1974.

On June 25, 1987, Bird received the National Medal of Science from Ronald Reagan (Figure 5), which I believe was a particularly meaningful award for him. In the award citation, Bird was recognized for "his profoundly influential books and research on kinetic theory, transport phenomena, the behavior of polymeric fluids, and foreign language study for engineers and scientists." His academic father, Joe Hirschfelder, received this award in 1975; and his academic grandfathers (co-advisors), Henry Eyring and Eugene Wigner, both received the National Medal of Science, Eyring in 1966 and Wigner in 1968.

Bird was elected to the National Academy of Engineering in 1969 for "Contributions to fundamental chemical engineering in the fields of transport phenomena and rheology;" he was elected to the National Academy of Sciences in 1989. As is fitting, he has been recognized numerous times by the American Institute of Chemical Engineers, winning the William H. Walker Award in 1962, the Professional Progress Award in 1965, the Warren K. Lewis Award in 1974, the Founders Award in 1989, and the Institute Lecturer Award in 1991.

Legacy

Bird has given and continues to give much to his profession and the students, coworkers, and others he has worked closely with. I doubt anyone has ever heard a lecture or seminar by Bird and not been struck by its beauty, organization, and clarity. His ability to organize and present material in textbooks has helped generations of engineers and scientists to learn new material. He has a great ability to draw out parallels among related concepts, to connect fundamentals across length scales, to illustrate difficult concepts through clearly explained examples, and to pose problems to help students better learn material at different levels of difficulty and complexity.

He has, of course, touched many people directly in his career. His academic "family tree" of direct descendants includes 40 PhD students at the University of Wisconsin. These are listed in Table 2. His first doctoral student was David Longmire (1957) who later went on to a career on Wall Street; his last PhD student was Jay Schieber, who is currently a professor of chemical and biological engineering and of physics at the Illinois Institute of Technology. We are all deeply grateful for the opportunity to have worked with Bob.

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