

John Tyler Bonner (1920–2019)

It seems strange to feel surprised by the news that someone has died just short of his 99th birthday, but that is the sort of person John Bonner was. One of the leading biologists of the 20th century, he remained active until the end. So much so, that he was eagerly awaiting a special issue of the *Journal of Experimental Zoology* being brought out in his honour¹. Fittingly, the finding that made his name had appeared in the same journal in 1947. By then he had completed a Ph D at Harvard and joined Princeton University, USA, where he spent his entire academic life. The finding had to do with the central step in the development of cellular slime moulds. They are microorganisms that are found worldwide in soil and animal dung, part amoeba, part plant and part animal. They have an unusual life cycle in which development is triggered once the food supply is exhausted. Bonner brought these fascinating creatures to the forefront of biology. He discovered that starved amoebae of *Dictyostelium discoideum*, their most commonly studied species, sent out a diffusible chemical attractant which made the amoebae come together and form a multicellular body². In 2016, he recalled how he felt when he realized that chemotaxis was behind the transition to multicellularity: ‘My Eureka moment had me dancing in the lab and punching the air... I knew I would get my degree then’³. Word of the unusual discovery got around; no less a person than Albert Einstein requested a private viewing of the film he had made⁴. Paul Weiss, one of the leading cell biologists of the time⁵, was convinced that rather than chemotaxis, the cells could be guiding one another via physical contact. Interestingly, in an illustration of the principle of ‘double assurance’ that seems to characterize biological processes, it turns out that cellular slime mould amoebae make use of contact guidance too⁶.

For the rest of his life Bonner continued to probe the mechanisms that made these amoebae come together, organize themselves into polarized cell masses, move with seeming purposiveness towards the surface, and once there, erect themselves into a ball of spores held aloft by a stalk of dead cells. Many of his early findings were striking. He termed one, the constancy in relative proportions

of cell types over a 10^5 -fold range of cell numbers, ‘the supreme problem in the differentiation of the cellular slime moulds’⁷. Later, working with a related slime mould, he showed that it was possible to short-circuit the normal life cycle by making cells bypass the feeding stage entirely (except once, at the beginning)⁸. It is astonishing how much of what we know about the behaviour of *D. discoideum* and related species comes from work carried out by him, singly or in collaboration. He was involved⁹ in identifying the chemical attractant responsible for chemotaxis in *D. discoideum* as cyclic AMP, the ubiquitous ‘second messenger’ in our bodies; that the same chemical forms a spatial gradient in the slug-shaped aggregate and induces cells to differentiate; that the slug is sensitive to light (phototaxis) and to astonishingly weak temperature gradients; (thermotaxis)¹⁰; that the difference between cells that survive as spores and cells that die as stalk is prefigured by intrinsic heterogeneities; that ammonia is a ‘spacing substance’ that keeps spore masses apart, as well as a substance that mediates phototaxis; that amoebae track bacterial food by chemotaxis too, this time directed towards folic acid released by bacteria. Over the years many asked the same questions he did and got the same answers, perhaps with added molecular detail¹¹.

Some of Bonner’s observations on the slime moulds cry out to be taken further. Two were made after retirement. He managed to create one-dimensional strings of amoebae; astonishingly, even

they showed a head-to-tail pattern of differentiation similar to normal aggregates¹². Later he came up with a way to generate two-dimensional multicellular masses in which the movements of the constituent cells could be easily monitored¹³. He was always a hands-on experimentalist; he said retirement allowed him to re-experience the joys of life as a graduate student, doing everything by himself, unburdened by responsibilities. He knew the ins and outs of cellular slime moulds, and possessed what Barbara McClintock called a feeling for the organism. The book he wrote about their development remains a source of inspiration for the manner in which he surveys the field, the phenomena he emphasizes and the questions he raises¹⁴.

In great measure due to him, these days it is common to include *Dictyostelium* among so-called model organisms. He saw it otherwise: ‘To me this way of thinking has always been deeply troublesome. My fascination with the experimental analysis of slime molds is based on the idea that one wants to find out about slime molds! Slime molds are a model system for the study of slime molds. If one reveals some activity or process that is shared with other organisms, then all to the good; but that is not the reason I have devoted my scientific life to slime molds. Rather, it was to see how slime molds work, especially in their development, and then to compare them to mammals and other vertebrates, to invertebrates such as nematodes and fruit flies, to fungi such as yeast, and to higher plants. The fact that each of them

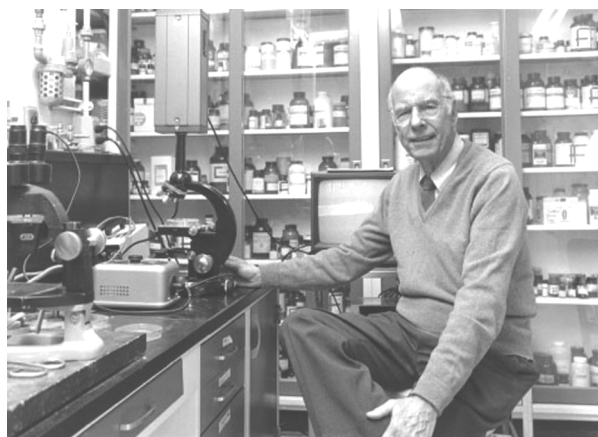


Figure 1. Portrait of John Bonner taken in his laboratory in Princeton University, USA, in 1990.

will have important differences and important similarities is to me the key issue. It is only by making a comparison of such diverse developments that we will have a genuine understanding of the diversity and the unity of life¹⁵.

Bonner's experimental methods mirrored those of Edwin Grant Conklin (1863–1952), Hans Driesch (1867–1941) and Ross Harrison (1870–1952). Like them, he depended almost entirely on elementary manipulations, vital dyes and careful observations. He decided to work on the cellular slime moulds when he realized that by doing so, he could combine a passion for the 'lower plants' with his desire to follow those greats of embryology¹⁶. The little biochemistry in the papers came from co-workers. He thought the molecular biology revolution had done wonders for biology, but preferred to remain a whole-organism biologist. There was no genetics in his work either, but then the sexual cycle of the cellular slime moulds is not easy to handle. He applauded mathematical modelling of developmental problems, though there is practically no mathematics in his work except in the first book¹⁷. He made as many original contributions through books as through publications in journals. In that respect he went back to a mode of scholarly communication that appears to have disappeared in the natural sciences¹⁸. The vast majority of the

papers were concerned with the minutiae of development in a small organism and short-term explanations. In the books he tackled major issues of evolution over long timescales; and development almost always figured in them¹⁹. By and large, the papers contained reports of experimental findings, while the books were almost entirely theoretical²⁰. The writings on evolutionary theory made Bonner's name in the wider world of biology. Each book inquired into a phenomenon from a slightly different perspective, and thereby added to the richness of the overall picture. C. H. Waddington's comment on the first one applies to all: '...provides an extraordinarily good review of most of the major problems involved in this complex matter. ... it is one of those scientific treatises, nowadays only too rare, which can be read for pleasure even by those not intimately familiar with its subject'²¹.

Three themes recur in the books. *One*, what evolves is the life cycle as a whole. Bonner stressed that phenotypes, on which natural selection acts, exist in four-dimensions. In other words, they vary in time. The static representations (e.g. embryo, larva, juvenile, adult) in terms of which we visualize organisms miss out on this²². Therefore, changes in the timing of gene action (heterochrony) can lead to altered relationships among life-cycle stages, and thence to evolution-

nary change²³. *Two*, the primary factor behind the evolution of complex forms is selection for size increase, which opens the way to division of labour and complexity²⁴. *Three*, the multicellular state is formally equivalent to a social group. Cell differentiation is comparable to division of labour in social groups; multicellularity and social life are both dependent on increasingly elaborate systems of communication²⁵. Two of the books, *The Evolution of Culture in Animals* and *Randomness in Evolution*, stand out. The first takes off from a then-radical definition of culture as the transfer of information by behavioural means. It goes on to argue that human culture has evolutionary antecedents, even in creatures without nervous systems²⁶. He goes further in the Gandhi Memorial Lecture 'Dividing the labour in cells and societies', and points out that division of labour goes up with size in multicellular animals, insect societies and human groups, but the parallel trends mask very different ways of exchanging information²⁷. *Randomness in Evolution*, his last scientific book, marked a radical turn. He had early recognized the importance of non-genetic variation in evolution, and – in several places – hypothesized that small and simple organisms were more tolerant of genetic mutations than large and complex ones²⁸. Now he extended it to suggest that the forms of microorganisms were often products of chance rather than selection²⁹. Coming from a lifelong selectionist, this looked like a major change in stance.

A part of the puzzle is solved when one goes back to the early books: there is an unusual aspect to Bonner's attitude to evolution. He admired Darwin (of course), but also D'Arcy Thompson, who did not think much of natural selection. That may seem odd, but Bonner's careful reading of the classic *On Growth and Form* must have made him see that its anti-selectionist stance was by no means anti-evolutionary³⁰. Also, when D'Arcy Thompson wrote that it is incorrect to visualize an organism as being made of more or less independently evolving parts, it struck a chord with him. It meant that the scope of what can evolve must be constrained by how existing forms are built, as well as the physical properties of what goes into building them. Indeed Bonner's first book, *Morphogenesis: An Essay on Development*, which came out in 1952, included discussions of how



Figure 2. Participants of the Mahabaleshwar seminar on modern biology on the theme 'Patterning in Biology' (Pachmarhi, India, October 1990). L-to-R, (i) standing: Aditi Pant, Raghavendra Gadagkar, X, X, X, Rohini Balakrishnan, John Bonner, Stuart Newman, X, Philippe de Reffye, X, Marc Jaeger, X, Raju Iyer, X, Dinkar Sahal, Madhav Gadgil, K. S. Krishnan, Vidyanand Nanjundiah, X, X, Sushil Kumar, Aparna Basu, Kei Inouye, V. Ramesh, X, Ramamurthy Baskar; (ii) sitting or kneeling: Maneesha Inamdar, Somdatta Sinha, K. S. Murali, X, Silanjan Bhattacharyya, X, X, X, Girish Deshpande, Bhupesh Saxena, Neeraj Jain, Preston Devasia.

mechanical properties and patterns of growth influenced form. It could have been D'Arcy Thompson writing for biologists (and non-linguists)³¹. Bonner immediately appreciated that in some cases generic physico-chemical mechanisms and self-organization might account for the origin of new forms, with genetic change coming about later to refine and stabilize the outcome³². He pioneered the contemporary interest in evolutionary–developmental biology. He saw not just that the phenomena of development make sense only in the light of evolution, but that a knowledge of developmental processes is necessary to understand evolution. Hall rightly says ‘...in his search for the origins of multicellularity in the behavior of slime molds [Bonner] was working on evo-devo before most of us were aware that the field was reemerging’³³.

He came more than once to India, on two occasions to attend conferences. The stories he told then were as captivating as the talks. A special memory is of evenings spent listening to Bonner and Tokindo Okada trade recollections of the days they spent together in Waddington’s lab. During one visit to Bangalore he was working on a book. People kept dropping in all the time; he invariably gave them the impression that he had been waiting for them. No wonder he was an instant hit with everyone. Bernd Würster, his postdoc in Princeton in the early 1970s, recalls ‘...fellow professors came to him with all sorts of problems. The question was usually “John, do you have five minutes?” Even knowing that five minutes was the unrealistic minimum, he always had time and took the petitioner into his office. One could not make out what they said to each other, but usually laughter was heard. Although John may not have solved the visitor’s problem, he often helped him to live with it’³⁴. His sense of humour persisted to the end. The journal to which he had sent his last scientific article sat on the submission. After several fruitless enquiries, he wrote to the editor that it would be nice to hear from them soon, because he was 97 and time was passing (the editor remained unmoved). And in a letter to me around then ‘...I am a bit more confused and forgetful but I do a pretty good job of imitating a normal person’. His Christmas greeting last year said: ‘What comes next is my ninety-ninth birthday. I have conflicted feelings about this. The bad part is the loss of mobility – I will never

run again, nor dance, unless my partner is strong enough to lift me... However it is not all bad. For instance, a kind person made me the perfect soft-boiled egg this morning for breakfast that kept me happy for the rest of the day’.

His wit, charm and readiness to engage made everyone who got to know him a member of the John Bonner fan club. Besides, he showed that science could be fun and deep insights could be conveyed in simple language. There cannot be many scientists of whom that can be said.

1. It is due to appear later this year with articles by Bonner and admirers.
2. He named it after a witch who enticed men. Bonner, J. T. and Savage, L. J., *J. Exp. Zool.*, 1947, **106**(1), 1–26; Savage supplied the diffusion theory in an Appendix. An earlier paper on the same organism, his first, was published in 1944 in the *American Journal of Botany*.
3. <https://reflectionsonpaperspast.wordpress.com/2018/01/19/revisiting-bonner-1947/>
4. A part of the film can be seen at <https://www.youtube.com/watch?v=bk-VhLJLG7ug>. Bonner said he spent the rest of his life trying to answer the questions Einstein had put to him. Years later a BBC TV film, “Professor Bonner and the slime moulds” made him known to the wider public.
5. And, it is said, the person who coined the term ‘developmental biology’.
6. Bonner acknowledged as much in his first book. It may operate later in the life cycle; see Umeda, T. and Inouye, K., *J. Theor. Biol.*, 2002, **219**, 301–308; Fujimori, T. et al., *Proc. Natl. Acad. Sci. USA*, 2019, **116**, 4291–4296.
7. Bonner, J. T. and Slifkin, M. K., *Am. J. Bot.*, 1949, **36**, 727–734; Bonner, J. T., *The Cellular Slime Molds*, Princeton University Press, USA, 1967, 2nd edn.
8. Bonner, J. T., Joyner, B. D., Moore, A. A. Suthers, H. B. and Swanson, J. A., *J. Cell Sci.*, 1985, **77**, 19–26.
9. Together with T. M. Konijn, J. G. C. van de Meene, D. S. Barkley and Y. Y. Chang.
10. Bonner, J. T., Clarke, W. W., Neely, C. L. and Slifkin, M. K., *J. Cell Physiol.*, 1950, **36**(2), 149–158. Astonishingly, a temperature difference of 0.0005°C between left and right – i.e. across about 0.1 mm – is sufficient to orient the slug.
11. Cox, E. C., Nanjundiah, V. and Würster, B., Foreword to *Researches on Cellular Slime Moulds*, Indian Academy of Sciences, Bengaluru, 1991.
12. Bonner, J. T., Compton, Cox, E. C., Fey, P. and Gregg, K. Y., *Proc. Natl. Acad. Sci. USA*, 1995, **92**, 8249–8253.
13. Bonner, J. T., *Proc. Natl. Acad. Sci. USA*, 1998, **95**(16), 9355–9359.
14. Bonner, J. T., *The Cellular Slime Molds*, 1967, Princeton University Press, USA, 2nd edn.
15. Introduction to *Researches on Cellular Slime Moulds* (IAS, Bengaluru, 1991). Okada says the same thing in an essay on the biology of eye lens regeneration and supports it with the following quote from Gardiner, D. M. and Bryant, S. V. (*Int. J. Dev. Biol.*, **40**, 797–805): ‘...comparative studies are necessary to observe the full range of developmental potential: investigating only one “ideal model” system is self-limiting if that system is derived, specialized or developmentally restricted’ (Okada, T. S., *J. Biosci.*, 2000, **25**(2), 133–141).
16. Bonner, J. T., *J. Biosci.*, 1999, **24**(1), 7–12.
17. Among the papers, the mathematical modelling in a paper on slug movement (Odell, G. M. and Bonner, J. T., *Philos. Trans. R. Soc. London, Ser. B*, 1986, **312**, 487–525) was by Odell. For another exception see footnote 2.
18. There were 18 books, of which two do not deal with science: *Lives of a Biologist* (Princeton University Press, 2002), a delightful autobiography with many stories about scientists, and a memoir of summers spent in Cape Breton, Nova Scotia, where Bonner went every year to write his books.
19. Even so, small organisms remained at the centre of attention. Bonner was a signatory on the powerful ‘Biologists’ Statement on Teaching Evolution’ drafted by H. J. Muller (*Bull. At. Sci.*, 1967, **23**(2), 39–40), which was issued when the teaching of evolution was illegal in some states of the USA.
20. Theoretical, not mathematical. Non-mathematical theories have played a significant role in biology and are likely to continue doing so, something that is not always appreciated.
21. *New Biol.*, 1953, **15**, 118.
22. He put together his thinking on the subject in several books, in particular *Life Cycles: Reflections of an Evolutionary Biologist* (Princeton University Press, 1993). The four dimensions are not to be confused with those referred to in the book *Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life* by Jablonka, E. and Lamb, M. J. (MIT Press, USA, 2005).
23. The root of the idea goes back to Haeckel (Hall, B. K., *Int. J. Dev. Biol.*, 2003, **47**, 491–495). Heterochrony and mechanical constraints are at the centre of Bonner’s analysis of variant morphologies in the cellular slime moulds (Bonner, J. T., *Am. Nat.*, 1982, **119**(4), 530–552).
24. This was not a re-statement of Cope’s rule in new language, but incorporated scaling and took into account the importance

- of intricacies that allowed for lineages in which the trend was size decrease – which was based on natural selection too. See Bonner, J. T., *Why Size Matters: From Bacteria to Blue Whales* (Princeton University Press, 2006).
25. These ideas were explored in *Cells and Societies* (1956), *The Evolution of Complexity by Means of Natural Selection* (1988) and *First Signals* (2000). Bonner's paper 'The origins of multicellularity' (*Int. Biol.*, 1998, **1**(1), 27–36) made an immediate mark. His favourites, the cellular slime moulds, were ideal, because they were at the same time multicellular organisms and social groups; Bonner, J. T., *The Social Amoebae: The Biology of Cellular Slime Molds* (Princeton University Press, 2008). A paper with R. Gadagkar highlighted parallels between social amoebae and social insects (*J. Biosci.*, 1994, **19**(2), 219–245).
 26. Bonner, J. T., *The Evolution of Culture in Animals*, Princeton University Press, 1980.
 27. An Honorary Fellow of IAS, he was in Bengaluru as Raman Professor of the Academy. Bonner, J. T., *Curr. Sci.*, 1993, **64**(7), 459–466.
 28. He called it range variation. Bonner, J. T., *Size and Cycle*, Princeton University Press, 1965.
 29. To his delight, he found that even here Darwin had anticipated him. Bonner, J. T., *Randomness in Evolution*, Princeton University Press, 2013.
 30. Cambridge University Press brought out an abridged edition edited by Bonner in 1969. Unlike the original, it can be read in bed.
 31. Today we see D'Arcy Thompson (1860–1948) as an advocate of the importance of mechanics and physical principles for understanding changes of form in evolution, a precursor of S. A. Newman and others. Medawar rates *On Growth and Form* very highly, yet falls short of appreciating its full importance (*Perspect. Biol. Med.*, 1962, **5**(2), 220–232).
 32. Newman, S. A. and Comper, W. D., *Development*, 1990, **110**, 1–18; Newman, S. A., *J. Biosci.*, 1992, **17**(3), 193–215. In Bonner's way of putting it, '[genes] seem to seep in unavoidably, a bit like my old chemistry teacher at school who used to wear both a belt and a pair of suspenders'. (*Life Cycles*, p. 89).
 33. Evo-devo stands for evolutionary developmental biology. Hall, B., *Int. J. Dev. Biol.*, 2003, **47**, 491–495. Hall dates the origin of the field to studies on comparative embryology fuelled by the publication of *The Origin of Species*.
 34. Bonner was Department Chairman at the time. Cox, E., Nanjundiah, V. and Wurster, B., Foreword to *Researches on Cellular Slime Moulds*, IAS, Bengaluru, 1991.

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Bhaskar Dattatraya Kulkarni (1949–2019)

Dr B. D. Kulkarni, popularly known as BD to his friends, and a well-known chemical engineer passed away suddenly at Pune on 14 January 2019. A true 'scientist–scholar' in every sense of the word, Kulkarni was an undisputed leader in the area of chemical engineering.

Born in Nagpur on 5 May 1949, Kulkarni earned his M Tech degree in chemical engineering from Laxminarayan Institute of Technology, Nagpur in 1972. He joined the National Chemical Laboratory (NCL), Pune in 1973 to pursue his Ph D work with L. K. Doraiswamy, and stayed there till the last day of his life. His doctoral research was on the subject of modelling of gas–liquid and gas–solid reactions, which led to the development of the delayed diffusion concept in chemical reaction engineering. Beginning his professional career as a Scientist C in 1979, he rose to the position of Deputy Director (2002–09), CSIR-Distinguished Scientist (2010–15), INSA Senior Scientist and a JC Bose Fellow in a stellar career spanning over 45 years. He was a complete home-grown product who never went out of India for education or scientific training. He transcended man-made boundaries in science and

technology because of his mastery over mathematics, which he used as a 'language' to successfully unite and make high-impact contributions in the physical, chemical, biological and engineering sciences. His ability to translate physical phenomena to mathematical models



which could be analysed to reveal interesting features that the human mind was incapable of comprehending, was widely acknowledged. His extraordinary intel-

lect coupled with his rich R&D experience gave him the uncanny ability to recognize patterns in results and data – those that could be universal and those that were unique to the phenomena – much to the astonishment of others. His work effortlessly traversed between deterministic and stochastic modelling, cutting across time and length scales.

This approach also made him recognize areas and problems that would be decades ahead of their time. For example, he realized that studying nonlinear systems, which are usually the real life and common place situation, required new and innovative algorithms for analysis. This set the course for his scientific contributions in the seventies. The synthesis of the pen-and-paper approach to arrive at nonlinear system models and subsequent use of computational methods of analysis, whereby the accuracy and speed of obtaining solutions could be improved led to studying of complex systems for their multiplicity, bifurcation, oscillatory and chaotic behaviour. It included studying the phenomenon of high-dimensional space–time pattern-forming systems by statistical quantifiers at a time when studies of nonlinear