A Fascinating Biography Of an Important Molecule

Heavy Water and the Wartime Race for Nuclear Energy

Per F. Dahl
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Reviewed by David C. Cassidy

When Ernest Rutherford hypothesized the existence of a neutral nuclear constituent in 1920, he suggested that it might lead to the discovery of heavier isotopes of hydrogen. Twelve years later, just as James Chadwick in Cambridge, England, announced the discovery of the neutron, Harold Urey and his colleagues at Berkeley announced almost simultaneously the discovery of deuterium, the first isotope to be separated from an element in pure form. Deuterium atoms, bound to oxygen, form deuterium oxide—better known as heavy water—which constitutes about one part per 4500 of natural water. Soon after the outbreak of war in Europe in 1939, the rare heavy water proved to be the optimal substance for the necessary slowing of fission-produced neutrons in a reactor using natural uranium.

Per Dahl, a former staff scientist at the Lawrence Berkeley Laboratory, who has written previously on the histories of the electron and superconductivity, provides a fascinating, broadly readable, technically accurate account of deuterium oxide—essentially the biography of a molecule—from its prediction and discovery to its production and uses in the race to unleash nuclear energy during World War II. Reminiscent of the passage of an exquisite Stradivarius from setting to setting in the recent film *The Red Violin*, Dahl traces his molecule from Berkeley and Cambridge to wartime fission researchers in Italy, France, England, Canada, the US, Germany, and, briefly, the Soviet Union and Japan. But a good deal of the story centers on Norway, which, well into the war, possessed the world's only heavy-water production plant. It is a story that, analogous to the film, contains a mixed cast of fascinating characters and events. And, similar to the violin painted in blood, the story of heavy water carried a sinister side. In addition to its central role in the acquisition of nuclear weapons, an estimated 120 people—commandos, guards, and civilians—died in its cause during the war.

For their part, the Americans chose ultra-pure graphite over heavy water as the neutron moderator for their main wartime reactors, principally because they lacked at first the production capacity for heavy water. But they did eventually produce heavy water on a massive scale and did construct heavy-water reactors as a backup. The Germans took the opposite approach: Deciding against graphite and the building of their own production facilities, they chose instead to rely on shipments of heavy water from the forced enhancement of production at the plant in Norway, then under German occupation. This left the German effort dependent on a foreign source that was vulnerable to sabotage and aerial bombardment, both of which occurred.

The reasons for this fateful decision, and for the ultimate failure of the German effort, are not quite clear from Dahl's account. German researcher Walther Bothe had measured a prohibitively high absorption cross section for neutrons in graphite, which was later attributed to the presence of impurities. But it is not evident why better tests for impurities were not made or why purer graphite was not obtained, even though Paul Harteck had argued to the authorities for both. Without elaboration, Dahl makes the novel assertion that, in any event, cross-section experiments were less important than "the economics of high-purity graphite on an industrial scale . . . [which] effectively eliminated carbon as a moderator in a German reactor."

Although the Germans were ahead of the Allies in fission research at the beginning of the war, they eventually fell far behind. The reasons for the failure of the German project to achieve even a chain reaction are well researched, if still hotly debated. Although he consulted a host of archival sources, Dahl's tendency to rely only on two secondary sources and one published postwar interview of the chief German scientist, Werner Heisenberg, leads at times to vagueness. For instance, Dahl remarks only in passing that, beginning in June 1942, German researchers displayed a sense of complacency and lack of urgency about fission research. This has been discussed at length in the literature as a symptom of underlying attitudes among the research leaders, especially Heisenberg, that hindered the German effort.

Nevertheless, Per Dahl has written an outstanding, fascinating account of the discovery and applications of heavy water in the wartime race for nuclear energy, one that specialists and the general public alike will find intriguing.

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Dynamic Earth: Plates, Plumes and Mantle Convection

Geoffrey F. Davies
Cambridge U. P., Cambridge, N.Y., 1999. 458 pp. $90.00 hc ($39.95 pb) ISBN 0-521-59067-1 hc (0-521-59933-4 pb)

Geophysicists divide Earth's surface into 10 (more or less) nearly rigid tectonic plates, which move with respect to each other at rates of a few centimeters a year. Plates move apart at midoceanic ridges. Trenches and island arcs occur at subduction zones, where plates converge. Horizontal motion without convergence or divergence occurs at transform faults, such as the San Andreas Fault in California. This hypothesis provides a unifying framework for solid-Earth science to the point that allusions to it appear even in TV ads.

The underlying dynamics of plate tectonics is not as well known, however, and, in *Dynamic Earth*, Geoffrey Davies fills this void with an excellent, modestly priced, and generally accessible book. Davies is well qualified to do this. He is a member of a group of scientists at the Australian National University who developed much of the modern synthesis of the underlying dynamics and geochemistry associated with global tectonics. His contributions include the relationship of convection within Earth to gravity anomalies and topography at the surface and the underlying processes beneath such hotspots as Hawaii and Iceland.

Davies begins with the history of his science, which is essential for understanding the development of current dynamic theory and the confusing nature of its terminology. Forty years ago, Earth sciences was mainly descriptive. Geologists since the late 1700s had developed a relative geological time scale, locally from positional relationships of rocks and globally from fossils. Beginning at the start of the 20th century, they forged an absolute scale.

It was commonly known that Earth had an eventful history, with mountains and their subsequent erosion being the most eye-catching feature. No one knew much about the underlying processes. Geophysicists had developed effective methods for remotely sensing the shallow subsurface and, on a global basis, had considered topics such as Earth tides and hydrostatic ellipticity, and they had determined the deep structure of Earth from seismic studies. Seismologists routinely detected and catalogued earthquakes, but they could not explain why more earthquakes occurred in some places than in others.

By 1970, plate tectonics had unified the concept of continental drift with the more recent concepts of seafloor spreading and subduction. The initial evidence for the hypothesis was largely kinematic, including magnetic stripes on the seafloor and the directions of fault-slip inferred from earthquake studies. The initial investigators learned much by just considering the geometry of the surface plates and their physics down to about 100 km.

In the modern synthesis, plate tectonics is a form of thermal convection. In fluid-dynamics terms, the oceanic plates are the upper thermal boundary layer, which founders into the mantle as slabs. The negative buoyancy of slabs and lateral temperature contrasts that exist at midoceanic ridges drive flow. The mantle cools slowly with time, and radioactivity heats it from within. Earth's core heats the mantle from below, giving rise to another feature of the modern synthesis: mantle plumes, which supply some 10% of the heat reaching the surface. Plumes are thin conduits formed by and carrying hot, low-viscosity material up from great depths. This hot mantle material impinges on the base of the plates, giving rise to hotspots. In the case of Hawaii, the plate moves relative to the top of the conduit, producing a series of volcanic islands. The process is analogous to a series of burns caused by moving one's hand slowly over a candle.

This is a general interest book on global Earth processes for the educated public, including K–12 teachers. Most of it is accessible to anyone having knowledge of high-school science. Davies clearly explains the way scientists dimensionally obtain the magnitude of physical quantities without having fully to solve complex problems. He provides concise vector calculus overviews of heat and mass transfer for the mathematically inclined. The book is quite usable as a gateway to the geodynamics literature or as an overview for other types of Earth scientists. Specialists will find valuable Davies's insights on geochemistry, plumes, and the effect of phase changes on convection.

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Small Worlds: The Dynamics of Networks between Order and Randomness

Duncan J. Watts
Princeton U. P., Princeton, N.J., 1999. 262 pp. $39.50 hc
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The term "small worlds" in Duncan J. Watts's book title refers to the observation that everybody is connected with everybody else through a short chain of acquaintances. A character, Ouisa, in John Guare's play *Six Degrees of Separation* makes the claim that we are all, presidents, gondoliers, and Eskimos alike, separated by only six other people. So the phenomenon is sometimes referred to as "six degrees of separation."

Computer scientist Brett Tjaden applied the same small-worlds idea to the links among actors who have performed in movies together. If you have been in a movie with Kevin Bacon, for example, then you have a "Bacon number" of one. If you have never been in a film with Kevin Bacon, but have been in a film with someone who has been in a film with Kevin Bacon, you have a Bacon number of two, and so on.

The first person to have his name associated with this small-worlds phenomenon is the great 20th-century mathematician and cofounder of probabilistic graph theory, Paul Erdös. People's "Erdös numbers" are a measure of how close they are to Erdös, via their coauthors; four hundred seventy-two people can boast an Erdös number of 1, since they have coauthored a paper with this prolific scientist. Of course, most people do not have Erdös numbers, since they are not scientists or mathematicians, so there is a limit to the applicability of the idea.

It is quite easy to understand the small-world idea: If each person knows, say 100 random others, each of whom know some 100 other random persons, then, obviously, in only 6 links each, each person connects with $100^6 = 10^{12}$ persons, which means that (almost) everybody in the world is connected by not only one but by very many paths of length 6 to one another.

This goes for random networks, or random graphs. However, we know that a lot of local clustering occurs. The caveman knew only his nearest neighbors, who also knew only their nearest neighbors. It is very likely that a lot of our closest friends are also our friends' closest friends. This makes the world "larger": More links are needed in order to reach everybody.

The extreme "large" world emerges if we consider people located on a simple d-dimensional regular lattice of a given large size, as for instance a one-dimensional ring of size N, on which everybody knows only his or her nearest neighbors. The maximum number of links between any two persons on the ring is $N/2$, which could be a very large number.

Most real networks are somewhere between the two extremes of randomness and order. We have some local connections, as in the ring model, but also some distant acquaintances. Duncan Watts's claim to fame is the introduction of a small number of random shortcuts into the ring model, which he described in a recent *Nature* paper he coauthored with Steve Strogatz of Cornell University. By tuning this number, one produces a phase transition, or rather a smooth crossover, between the small world represented by the random network and the large world represented by the lattice. Watts and Strogatz argued that three disparate systems—the neural