On the trail of the transistor

Crystal Fire: The Birth of the Information Age

by Michael Riordan and Lillian Hoddeson
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Frederick Seitz

For a quarter of a century, Lillian Hoddeson, a physicist, has collected background material on the history of solid-state physics, both basic and applied, carrying out taped interviews with many of the most creatively active scientists, and studying the available literature, including archival files. One of the many by-products of this endeavour has been the multi-authored book *Out of the Crystal Maze* (Oxford University Press, 1992), of which Hoddeson was co-editor and leading catalyst.

Early in this decade, and in recognition of the fact that 1997 would be the fiftieth anniversary of the invention of the transistor, she joined with Michael Riordan, another physicist with a comparable interest in science history, to produce this lively account of the invention, with much emphasis on events that preceded and followed it. The background, personalities and actions of the principal actors are given ample coverage.

Mervin Kelly, who became head of the Bell Telephone Laboratories in 1936 and remained its leader for more than 20 years, can clearly be said to be the spiritual father of the transistor. While head of the vacuum-tube division of the Western Electric Company, also a subsidiary of AT&T, he noted in the late 1920s the remarkable, durable properties of inexpensive copper-oxide rectifiers, commonly used at that time for the conversion of relatively low-frequency alternating current to direct current. Among many virtues, they needed no heated filament to provide conduction electrons. He decided that the company should see if it could develop a comparable semiconductor triode.

Others might similarly ponder this matter, but Kelly would eventually gather together the appropriate combination of resources to achieve success. Once he became head of the laboratories, he took steps to increase the size of the group involved in solid-state research, which already contained Walter Brattain and Gerald Pearson. William Shockley was one of the first additions.

Unfortunately, Kelly's ambitious dream had to be all but shelved until 1945 because of the more immediate pressures of war research. In the meantime, however, much attention was devoted to the relative perfection of silicon and germanium diodes for use as 'mixers' in microwave radar — a development started in England and carried on in several laboratories in the United States, including the Bell Laboratories. Two new, versatile and more

John Bardeen, William Shockley and Walter Brattain (left to right) at Bell Telephone Laboratories in 1948. The picture appears in *The Invention that Changed the World: The Story of Radar from War to Peace* by Robert Buder, reviewed by Frederick Seitz in *Nature* 384, 424 (1996) and now published in the United Kingdom by Little, Brown at £20.

thoroughly understood semiconductors had become available for exploratory research.

With the end of the war, Kelly appointed Shockley as head of a team attempting to develop a triode. Fortunately, Shockley succeeded at this time in adding John Bardeen to the group. Bardeen had taken leave of an academic post in physics for military research early in the war and found the new programme in solid-state physics particularly challenging. He possessed two very valuable gifts: he had the tenacity of a bulldog when attacking a difficult problem and he possessed a remarkable 'third eye' which provided him with special insight into complex problems. His advent proved to be critical for the immediate course of the programme.

Early on, Shockley had tried to develop what is now known as a field-effect transistor in the most direct way, namely by attempting to alter the number of conducting carriers (electrons or holes) in a strip of semiconductor carrying a current by applying an external field normal to the strip, much as one might alter the charge in a condenser plate. The experiment failed.

Shockley, temporarily discouraged, turned the problem over to Bardeen and Brattain, who had developed a working partnership, while he turned to other solid-state problems. This was in fact one of Shockley's most creatively productive periods in relation to more general aspects of solid-state physics.

Bardeen and Brattain decided to try to

understand the factors that had caused Shockley's experiment to fail. Bardeen guessed that the specimen of semiconductor possessed surface trapping levels for the conducting carriers and that the occupation of these could vary in such a way as to compensate for variations in external applied field. With the aid of colleagues, they were able to prove that this was the case, opening the way to the eventual development of field-effect transistors.

Then, in re-examining a different failed experiment carried out in connection with the study of trapping levels, they made a remarkable discovery. When a current of minority carriers was injected from a point-contact electrode and induced to flow to a nearby point-collecting electrode, both that current and one of majority carriers from the collector to a third, more distant electrode (the base) could be modulated by altering the potential of the base. The invention of the bipolar point-contact transistor followed. It was demonstrated to management on 23 December 1947.

Because the invention was founded as much on empirical observation as on theoretical understanding, several issues about the operation of the device had to be explored. Among the most important, John Shive soon demonstrated that minority carriers actually can travel considerable distances through bulk material where majority carriers dominate. The minority current was not confined to a

thin depletion area at the surface, as Bardeen thought might be the case.

Shive's demonstration caused Shockley to propose an important modification of the original transistor. Instead of injecting and collecting minority carriers with the use of point contacts, one could employ relatively large area p-n junctions and gain the advantage of much larger currents. The concept of the bipolar junction transistor, which was to dominate the field for the next two decades or so, was born. A semiconductor triode was not only feasible but was about to generate one of the greatest technological revolutions in history.

The text is rich in anecdote, presenting the reader with colourful views of many of the secondary as well as the primary figures involved. Backgrounds, hopes and destinies are examined. Matters such as Shockley's gradual change in personality as he became a celebrity, and the changes in the working atmosphere which made Bardeen decide to return to an academic career, are dealt with in a forthright manner.

Although the book is written in a semi-popular style which should appeal to the type of general reader interested in the history of technology, the historical research on which it is based is impeccably sound, unlike many books of this kind. The authors, with their professional reputations involved, have left no stone unturned in making their work an enduring classic. □

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Ceaseless fluctuations

Conceptual Developments of Twentieth Century Field Theories

by Tian Yu Cao

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Ian Aitchison

A century can be a convenient unit of history. During the past hundred years or so, quantum field theory has replaced classical mechanics as the framework of fundamental physics. The climax of this development has been the spectacularly successful Standard Model, a relativistic quantum gauge field theory describing matter and forces at the smallest sizes currently accessible.

But the intricate theoretical structure has imperfections, and the general quantum field framework has failed to accommodate gravity on the same footing as the other known forces. There are tantalizing hints of a new physics beyond quantum field theory. It seems a good moment to take stock.

Tian Yu Cao's timely book provides a broad overview of twentieth-century field theories. The story is presented in three parts, each devoted to a general line of development which he subsumes under the heading of a "research programme".

The first part covers the geometrical programme (Einstein's metric field theory of gravitation, and its developments); the second

concerns the quantum field programme (the emergence, formulation and application of quantum field theory, including current algebra, anomalies, renormalization and the renormalization group); and the third describes the gauge field programme (the Standard Model, and some extensions). The discussion is on occasion necessarily technical, but this is not an advanced physics textbook: rather, it is an up-to-date, well informed and detailed historical account of the conceptual origins and development of twentieth-century field theories, structured in terms of the above programmes.

This is not all, however. Surrounding this substantial historical meat are introductory and closing chapters that are philosophical in character. For me, they are the most stimulating parts of the book.

Cao's aim is to show that there is a pattern in the conceptual evolution that he describes. In particular, he is concerned to combat the claim, originating in the work of Kuhn and others, that the history of science reveals no coherent direction of ontological development, and hence that no theoretical ontology can be taken as the real ontology of the world. Or, in other words, no matter how empirically successful our succeeding theories may be, they do not provide access to metaphysical reality. The contrasting position that Cao wishes to defend is characterized by him as "structural realism" which, roughly speaking, holds that the structural relations between entities (often expressed by mathematical structure) in a successful theory should be taken as real, rather than the entities themselves.

For this enterprise to succeed, Cao must show that structural properties of theoretical ontologies do persist across conceptual revolutions. This requirement, together with a desire to defend the rationality of scientific growth, leads him to propose that scientific revolutions can occur by what he calls "ontological synthesis", in which an outmoded ontology survives as an epiphenomenon, derivable from a later and more fundamental ontology. Like most physicists, I am all in favour of realism and rationality, but, while I applaud Cao's attempt, I think his analysis is open to serious challenge.

Classical field theory arose from the need to explain how physical actions, such as gravity and electromagnetism, can apparently be transmitted between bodies some distance from each other; this is in contrast to mechanical actions, which occur by direct contact. Newton hated the idea of action at a distance; and even Maxwell, whose equations for the dynamics of the electromagnetic field are now part of the Standard Model, thought his equations described the dynamics of a mediating medium, the ether, which he took to be some sort of mechanical substance. The ontological shift, by which the field became established as a non-mechanical entity in its

The magic of mushrooms

Life may be too short to stuff a mushroom, as the writer Shirley Conran said, but make time to read all about them in Elio Schaechter's funny and fascinating book, *In The Company of Mushrooms: A Biologist's Tale* (Harvard University Press, \$24.95, £16.50). Fungi have been found in fossilized wood 300 million years old, yet they are more closely related to animals

than to plants. And there's no shortage of them: Schaechter estimates that there are about two tons of fungi for every human being on Earth. Vital in the kitchen, fungi play an even more important role in recycling. "Life on earth as we know it would be impossible without them," he says. So we'll have to forgive them for Dutch elm disease and the Irish potato famine.