THE MIDWEST JUNTO FOR THE HISTORY OF SCIENCE
Norman, OK, March 25-27, 1994

Concepts and instruments: the *potential* from Green to Kelvin

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Celebrating Green's achievements

Last year marked the bicentenary of the birth of the English mathematician and physicist George Green, who was born in Nottingham and died there forty-eight years later. His name is familiar to mathematicians and physicists through the textbook labels for two of his creations: Green's theorem and Green's functions.

Despite the importance and influence of his work, Green has remained to this day an obscure and enigmatic figure because of the peculiar circumstances of his life. His name and ideas might have altogether vanished from the history of science, had it not been for the fateful rediscovery of his first and most influential paper by William Thomson (later Lord Kelvin) some four years after Green's death.

Green was the son of a Nottingham miller and baker. He labored at his father's mill for many years, while studying mathematics and physics on his own. Since he was virtually isolated from the intellectual world of his time, one wonders how a man in those circumstances could not only have found the energy and inspiration to master the new sophisticated concepts and techniques of the contemporary French school of mathematical physics but to also expand their content and scope. This he did at a time when those new ideas were just beginning to enter the conservative mathematical establishment of Great Britain.

In this brief communication I shall not attempt to give an account of Green's life and accomplishments. Such may be found in a valuable and interesting biography by Mary Cannell, which appeared last year as part of the bicentenary commemorations. I just would like to share with you some reflections on a lecture Freeman Dyson gave on that occasion. Paralleling Dyson's approach, I will use Green's work for discussing matters of current interest in the history and philosophy of science.

Dyson concentrates on only one of Green's inventions, the Green's functions. He traces the story of this mathematical tool from classical physics, to its revival as a revolutionary instrument in quantum field theory in 1948, and to its present uses in particle physics and condensed matter theory. In the process he manages to convey a condensed, personal account of the development of quantum electrodynamics, a warm and appreciative semblance of his friend and mentor Nicholas Kemmer, and a brief but sharp indictment of the Ph.D. system of graduate education. Dyson delivers this bountiful fare in that lucid and engaging manner that we have come to expect from him.

Concepts and instruments

There is another point in Dyson's essay that is the subject of these reflections. Speaking of Green's functions, Dyson offers some provocative observations on what he sees as contrasting roles for concepts and for tools in the history of science:

> The second theme that George Green's work exemplifies is the historical fact that scientific revolutions are more often driven by new tools than by new concepts. Thomas Kuhn in his famous book, The Structure of Scientific Revolutions, talked almost exclusively about concepts and hardly at all about tools. His idea of a scientific revolution is based on a single example, the revolution in theoretical physics that occurred in the 1920s with the advent of quantum mechanics. This was a prime example of a concept-driven revolution. Kuhn's book was so brilliantly written that it became an instant classic. It misled a whole generation of students and historians of science into believing that all scientific revolutions are concept-driven. The concept-driven revolutions are the ones that attract the most attention and have the greatest impact on the public awareness of science, but in fact they are comparatively rare. In the last five hundred years we have had six major concept-driven revolutions, associated with the names of Copernicus, Newton, Darwin, Maxwell, Einstein and Freud, besides the quantum mechanical revolution that Kuhn took as his model. During the same period there have been about 20 tool-driven revolutions, not so impressive to the general public but of equal importance to the progress of science.

At first glance, this analysis would appear like an unfair criticism of Thomas Kuhn's work. After all, Kuhn is also the author of papers like "Energy Conservation as an Example of Simultaneous Discovery (1959) and "Mathematical versus Experimental Traditions in the Development of Physical Science" (1976), where instruments loom large. We must give him credit as one of the first historians of science to insist on treating scientists as practitioners, who learn their trade more through the instrumental practice of problem solving than from conceptual indoctrination. But it would also be unfair to Dyson to pursue here the defense of Kuhn. Dyson did not have an opportunity to develop his position beyond some brief remarks.

I find Dyson's observations valuable, thought provoking, and deserving a sympathetic response. I would like to show that they point to genuine problems in the history of science and to call your attention to the importance of some current work that addresses some of these problems. By pursuing the matter in this spirit I offer homage to both Dyson and Green. Dyson cites two examples of tool revolutions, one resulting from Galileo's use of the telescope and the other from the application of X-ray diffraction to molecular biology. He adds Green's functions to the list:

> The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained. In physics there has been a preponderance of tool-driven revolutions. We have been more successful in discovering new things than in explaining old ones. George Green's great

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> discovery, the Green's function, is a mathematical tool rather than a physical concept. It did not give the world a new theory of electricity and magnetism or a new picture of physical reality. It gave the world a new bag of mathematical tricks, useful for exploring the consequences of theories and for predicting the existence of new phenomena that experimenters could search for. The Green's function was a tool of discovery, like the telescope and the microscope, but aimed at mathematical models and theories instead of being aimed at the sky and the microbe.

Dyson appears to contrast concepts and instruments as mutually exclusive categories and to favor the thesis that, at least during revolutionary turns, new concepts are advanced for explaining previously known phenomena, whereas new instruments are mainly deployed for uncovering new phenomena.

Concepts and instruments tend to divide their labor in this fashion. But the crucial question is: do they always do it? Are there perchance revolutionary cases where their roles are reversed, where new concepts are instrumental in uncovering new phenomena or new tools prove essential in reaching explanations of previously known phenomena? The answer is not to be sought in philosophical speculation but rather in the search for historical facts. Luckily for us, much of it has already been done, and the answer, I believe, is affirmative. New concepts serve to disclose new phenomena; new tools are occasionally required to advance certain explanations. Sometimes concepts and tools do their jobs simultaneously and in close collaboration. Through a dynamical, dialectical interaction instruments beget new concepts and concepts become embedded in the design of new instruments. This can be shown through one single example, taken from another of Green's contributions: his potential function.

Energy: a conceptual and instrumental revolution

The potential function played a minor but significant role in one of the greatest scientific revolutions of all time, the so-called "second scientific revolution" of the 19th century. It proceeded by dismantling the entire structure of mathematical physics, which was then organized around the static conception of "force,",and by restructuring it completely around the new, dynamical notion of "energy" that emerged in mid-century. Among others, Crosby Smith and M. Norton Wise, separately and in their monumental joint biography of Lord Kelvin, have made great strides in disentangling the web of interacting factors — conceptual, instrumental, economic, technological and philosophical — that went into making the new energy physics. Here the briefest of sketches must suffice.

Three separate research lines converged finally in Lord Kelvin's instrumental concept of energy. Green's Essay of 1828 builds on the work of the great French mathematical physicists of the 18th century. This first line of research was a program for the reduction of all physical phenomena to the action of attractive or repulsive forces between point-like atoms. To extend it beyond the scope of the received Newtonian mechanics of masses and gravitational forces a variety of hypothetical "imponderable" fluids had to be created: electrical, magnetic, caloric (heat), etc.

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Another parallel tradition, which included experimenters like Borda, Coulomb and Faraday, sought to describe quantitatively, through the invention of sophisticated instruments and measuring techniques, the interactions and transformations of those hypothetical fluids. Their work led to a vague but almost universal conviction of the reciprocal interconversion of all the "forces" of nature.

The third and most important research line is that of the engineer-scientists that prospered at the École Polytechnique and other novel institutions under Napoleon I. Their efforts, exemplified by those of Sadi Carnot, were directed at measuring and improving the efficiency of machines and led them naturally to the central concept of work, under such rubrics as "mechanical effect."

In his 1828 Essay Green formally introduced the potential function. Gauss did independently the same in 1840. With hindsight we recognize it working sotto voce throughout the 18th century, from Euler to Lagrange. The potential describes the spatial distribution of masses or charges in such a way that the function's rate of decrease in the direction of a given point (its gradient in present language) yields the value of the force that would act there on a unit mass or charge. Although Green did not discover this function he was the first to realize its potential (no pun intended) as a tool for solving a great variety of problems in electrostatics.

Some 17 years later, Green's instrument of calculation was transformed into a fundamental explanatory concept, when Lord Kelvin identified the potential energy of a system with a quantity obtained by multiplying the potential function by the masses or charges. In 1851 Rankine formally introduced the concept of potential energy as the work stored in the configuration of a system, but Kelvin was effectively using this notion by 1845. Potential energy, kinetic energy, and work were defined operationally as mathematical relations between quantities reified by meter readings. This definition led Kelvin to articulate what is basically our present concept of energy, in terms of conservation and dissipation. The integration of the potential function into the general concept of energy thus affords a good illustration of a tool that became a source of conceptual explanations for many known phenomena.

I would like to end with a brief illustration of the reciprocal case, that of a conceptual innovation working as an instrument for the unveiling of new phenomena. Sadi Carnot used his ideal machine to establish by purely conceptual means an absolute upper limit on the efficiency of all possible engines. Kelvin, who was as much at home in mathematical physics as in the creation and design of measuring instruments, was able to look at Carnot's machine in an entirely new light, as an ideal thermometer.

Armed with this gedanken instrument he created the absolute scale of temperatures that, beyond its instrumental role in the standardization of physical units, worked in the discovery of new physical phenomena. Kelvin's scale made possible the extension of temperature measurement to electromagnetic phenomena and this, via spectroscopy and Planck's study of black body radiation, eventually led to the exploration of the quantum world.

These reflections only begin to scratch the surface of our subject. They are not intended as a refutation of Dyson's observations but rather as an indication of the need to refine and extend them. They are also an invitation to look into the work of Smith, Wise, Heilbron, Grattan-Guinness, and other authors whose researches are connecting the interaction of concepts and instruments to the rise of scientific technology and the economical structures of industrial society. Their work holds the promise of a new synthesis and of bridging the scandalous insularity still reigning in science, technology and social studies.

NOTES

1. "An Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism" reprinted in Mathematical Papers of the Late George Green, N. M. Ferrers ed. Paris: Hermann 1903, appeared in a very limited edition in 1828 and had no influence until Kelvin discovered it almost accidentally. On the eve of his departure to Paris to study with Regneault, Kelvin mentioned to his tutor Hopkins that he had found an interesting reference to the Essay, and that he had not been able to find a copy anywhere. Hopkins happened to have three copies and gave two of them to the young Kelvin (he was then 21), who took them to France. Green's essay made a great impression on Kelvin and, through him, on Liouville and Sturm. Whittaker in his classic *A History of the theories of Aether and Electricity* (2nd. ed., London, 1951, p. 153) says: "It is impossible to avoid noticing throughout Kelvin's work evidence of the deep impression which was made upon him by the writings of Green. The same may be said […] of Stokes; and indeed, it is no great exaggeration to describe Green as the real founder of that 'Cambridge School' of natural philosophers of which Kelvin, Stokes, Rayleigh, Clerk Maxwell, Lamb, J. J. Thomson, Larmor and Love were most illustrious members in the latter half of the nineteenth century."

2. Cannell 1993, the biography, has an appendix where M. Thornley clearly describes the mathematical innovations in the Essay. Cannell and Lord 1993 is a good summary.

3. An edited version of this talk was published in Physics World. (See Dyson 1993.)

4. There is implicit in Dyson's remarks a classification of instruments into physical and symbolic. Although concepts are not literally "instruments," the metaphorical extension is fruitful because concepts may have instrumental uses, and what makes something into an instrument is precisely its use. Analogously, physical objects may in turn have "conceptual" properties. D. de Solla Price has remarked that some instruments, such as astrolabes, were designed as embodiments of conceptual structures. For more on this point see my paper, Fernandez 1988.

5. *Energy and Empire* (Smith and Wise, 1989), obviously a synthesis out of many years of research, is essential reading for anybody interested in Kelvin and in the relations of physics, technology and society in the 19th century.

6. Heilbron 1993a gives a brilliant account of this line of research in 18th century France.

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