

How to make an educated guess

The Art of Insight in Science and Engineering: Mastering Complexity

Sanjoy Mahajan
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Reviewed by Adam Lidz

Enrico Fermi famously estimated the energy yield of the first fission bomb at the Trinity test site by dropping bits of paper and observing their deflection as the bomb's blast wave swept past. That anecdote provides a vivid example of the power of estimation. Although physicists widely recognize the utility of back-of-the-envelope calculations, current physics courses provide surprisingly little instruction and practice in that invaluable art.

Sanjoy Mahajan's *The Art of Insight in Science and Engineering: Mastering Complexity* is an antidote to that issue. It is a unique and entertaining tour of methods for estimating the solutions to complex problems. Under Mahajan's skillful guidance, readers assemble a powerful toolbox of techniques, which are illustrated and developed for application to a diverse range of fascinating topics. After working through the book, readers will feel equipped to come up with rapid-fire, approximate solutions to unfamiliar and complex problems, to pose their own questions, and to explore.

Mahajan draws from his extensive teaching experience, which includes courses at MIT and the Franklin W. Olin College of Engineering in Massachusetts. He also was inspired by his work as a graduate teaching assistant for the Order of Magnitude Physics class at Caltech taught by renowned astrophysicists Peter Goldreich and E. Sterl Phinney. Mahajan is also the author of a related book, *Street-Fighting Mathematics: The Art of Educated Guessing and Opportunistic Problem Solving* (MIT Press, 2010). The new book is published under a Creative Commons license, which means it can be freely redistrib-

uted or downloaded. In fact, in my own estimation-physics class, I used an early version that I obtained from the author's website.

The Art of Insight in Science and Engineering is organized into three broad sections and nine chapters, each illustrating different problem-solving techniques. Throughout, Mahajan poses, and subsequently answers, questions that readers can work through independently to help build their proficiency. In addition, numerous exercises are included for further practice.

In the first section, "Organizing Complexity," Mahajan introduces the divide-and-conquer strategy for breaking up estimation problems into several tractable subproblems. One illustrative example explores how many barrels of oil are imported into the US each year. Readers can estimate the amount of US oil usage from cars, the population of the US, the typical number of miles each person drives in a year, the gas mileage, and the volume of an oil barrel. Another approach described in that section involves conducting simple experiments around the home: For example, a person can estimate his or her maximum mechanical power output by timing a run up a flight of stairs. Also discussed is reasoning by analogy, exemplified by comparing spring-mass systems with electrical RLC circuits and thermal systems.

The second section, "Discarding Complexity without Losing Information," covers the use of symmetry principles and conservation laws, scaling relations, and dimensional analysis. It discusses characteristic atomic and molecular binding energies and size scales; it also covers solids, their elastic moduli and sound speeds through them. The author presents an approximate analysis of fluid drag forces, which is a powerful and ubiquitous example. The fluid drag analysis is applied to estimate the maximum speed of a cyclist on flat ground, the gas mileage of an automobile, and the power expended in the flight of birds and airplanes. In one classic application of dimensional analysis, Mahajan estimates the first fission bomb's energy yield from time-stamped blast photographs of the event and a corresponding scale bar.

The final section, "Discarding Complexity with Loss of Information," starts with a declaration: "When the going gets tough, the tough lower their standards: Approximate first, and worry later." The chapters include "Lumping," in which varying quantities are approximated by their typical or characteristic values, and "Easy Cases," such as considering a system's behavior in simple, limiting circumstances. The author discusses a wealth of interesting topics, including piano and xylophone physics, acoustic monopole radiation, electric dipole radiation—with a discussion of blue skies and red sunsets—gravitational radiation, the size of neutron stars, the time required to bake a fish, and the temperature of the Sun's core.

The Art of Insight in Science and Engineering is a wonderful and fun book that fills a gap in existing science curricula. I would recommend it as a primary text for an estimation class or as a valuable supplement for other science and engineering courses. It provides an enjoyable read for a broad audience and it should be comprehensible to first-year science and engineering students, although certain aspects may be fully appreciated only by more advanced readers.



Big Science Ernest Lawrence and the Invention That Launched the Military-Industrial Complex

Michael Hiltzik
Simon & Schuster, 2015. \$30.00
(528 pp.). ISBN 978-1-4516-7575-7

The intertwined development of what came to be called Big Science and of the military-industrial complex is important for physics practitioners and educators to understand because it helped shape research in their field. And two of the most fascinating characters in the tale—Ernest Lawrence and the particle accelerator—are worth celebrating.

So what does Michael Hiltzik, a Pulitzer Prize-winning journalist, have to say about those important topics in his new book, *Big Science: Ernest Lawrence and the Invention That Launched*

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the Military-Industrial Complex? According to him, Big Science was born on the very day in 1929 that Lawrence invented the cyclotron. Scientists' desire to use and improve the invention, plus Lawrence's optimism and management skills, led to Big Science's multidisciplinary research style, with its reliance on engineers and industrial involvement.

The military gets into the mix with the atomic bomb project, which in Hiltzik's telling was driven at every turn by Lawrence and his invention. To show how the military-industrial complex and Big Science grew in tandem—and how that made some question Big Science as a quest for knowledge—Hiltzik highlights the advent of what is now Lawrence Livermore National Laboratory and the development there of the hydrogen bomb. He ends by wondering whether the 1993 cancellation of the Superconducting Super Collider was “a death knell for Big Science,” and he notes that in the years since, “the dominant patron” of Big Science “is business” and that its future “appears to depend on industry.” To dramatize how Lawrence's influence still endures, Hiltzik includes a description of the 2012 discovery of the Higgs boson at CERN's Large Hadron Collider, which the author imagines is partly composed of cyclotrons.

But let's look at what actually happened. Starting in the 1930s, the increasing size and complexity of particle accelerators did lead to larger-scale efforts, most notably at the Cavendish Laboratory in the UK and at Lawrence's Radiation Laboratory (now Lawrence Berkeley National Laboratory) at the University of California, Berkeley. Also, by all accounts, Lawrence in particular celebrated the grand: He became famous for spearheading the rapid construction of ever-larger accelerators built with industrial and philanthropic support by project teams that included engineers.

Indeed, Lawrence and accelerator technology were important to the atomic bomb project: He provided technical advice to the military, and one of the Berkeley cyclotrons was used to discover fissionable plutonium. But Lawrence was not the most important wartime scientist. And accelerators were not the stars of the Manhattan Project—those would be the first atomic bombs and plutonium-producing reactors. It was World War II and the associated radar and atomic bomb projects—not accelerator-based research—that



forged the collaboration of scientists, major industries, and the military and that led to the consequential gigantic increase in the research scale.

However, after the war, no one was more important than Lawrence in shaping the new research system with its military and industrial connections, and no device was more central to that process than the accelerator. Before the war ended, Lawrence leveraged military contacts to obtain federal money to fund his Radiation Laboratory and to build accelerators of unprecedented scale, including ones that would be used to make exciting particle discoveries.

Following the war, a new federally sponsored national laboratory system emerged that boasted the world's largest accelerators. In the midst of the Cold War, those devices and the intellectual accomplishments they enabled came to symbolize technological prowess, military strength, and the cultural benefits of a free society. By the time of his death in 1958, Lawrence had also set other trends in the national laboratory system. The Radiation Laboratory sponsored both basic and applied research in a wide range of fields. Moreover, his founding of the Livermore laboratory continued the partnership of scientists with the military and added heft to the defense portion of the national laboratory system. The postwar national laboratory amalgam Lawrence had been instrumental in forging thus joined Big Science—so called because it relied on accelerators, teams, and price tags that grew ever larger—with the continued collaboration of scientists and the military-industrial complex.

Lawrence also paved the way for the era of “New Big Science.” With the end of the Cold War and the cancellation of the multibillion-dollar Superconducting Super Collider, the new, more bureaucratic federal patron demanded exacting justifications, and the esoteric agenda of Big Science fell out of favor. At that point, the multidisciplinary, accelerator-centered laboratory system that Lawrence helped shape smoothly shifted to the current system in which large accelerators serve a vast constituency of users who often work in small teams on projects with practical applications. Industrial partners help pick up some costs, but military support is minimal, since defense laboratories now have their own resources.

Hiltzik is a wonderful wordsmith, and he uses some good sources. Thus the book contains many readable and

accurate anecdotes about Lawrence. In addition, Hiltzik raises worthy questions about how military and industrial sponsorship have shaped and arguably compromised physics research. He is also right that Lawrence was important to the development of Big Science.

What a shame then that many factual errors and exaggerations undermine the book's value. Hiltzik incorrectly explains how the interrelationships linking Big Science, the military, and industry developed and played out. Worst of all, he misses what is most impressive about Lawrence's legacy—that he paved the way for the New Big Science. I wanted to like this book, but I simply cannot recommend it. Lawrence and accelerators deserve true celebration.

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Thermodynamics For Physicists, Chemists and Materials Scientists

Reinhard Hentschke
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Thermodynamics can be a tough sell in the classroom. “Many of us associate thermodynamics with blotchy photographs of men in old-fashioned garments posing in front of ponderous steam engines,” writes Reinhard Hentschke in the preface to his new textbook, *Thermodynamics: For Physicists, Chemists and Materials Scientists*. Hentschke is a professor of theoretical chemical physics and a practitioner of thermodynamics. His research expertise in soft-matter physics informs many of the examples that bring the book to life. With this volume of concise theoretical developments and numerous, detailed applications, the author shows that mastering thermodynamics is indispensable for understanding properties and processes at finite temperature. It should provide ample motivation for students hoping to contribute to the development of new materials and technologies.

The book's seven chapters can be roughly divided into four sections: introduction to thermodynamics, phase equilibria and phase transitions, statistical mechanics and computer simulations, and nonequilibrium thermodynamics. The introduction to thermodynamics follows the traditional route, from the concepts of work and the laws of thermodynamics to formal definitions of