ceptance, must be resolved to enable truly large-scale deployment.

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Data Volume Is Fourth Frontier in Astrophysical Observation

Martin Harwit's article "The Growth of Astrophysical Understanding" (PHYSICS TODAY, November 2003, page 38) was enjoyable and insightful. The author names three frontiers in observation: angular resolution, timing, and spectrometry. I propose a fourth: expanding data volumes. This frontier has progressed steadily, from paper-and-pencil catalogs, to photographic plates, to large-format CCDs and robotic survey telescopes.

Each advancement brings new discoveries. Some examples: Tycho Brahe's measurements of the planets were precise, but also voluminous; he had 85 data points on Mercury's orbit, for example—a great advancement on the state of the art. The volume, as much as the precision, made Johannes Kepler's analyses possible. John Goodricke discovered one variable star in 1784, but Henrietta Leavitt, working with thousands of stars on photographic plates, discovered the Cepheid period–luminosity relation. Today, in one of many superb examples, a huge observing project called the Sloan Digital Sky Survey is making precision measurements of large-scale structures. The project's resolution and spectroscopy are up to date, but its multiterabyte data set is really new and exciting.

Bigger and bigger surveys are absolutely necessary for advancing our knowledge of astrophysics. They provide the opportunity to discover extremely rare phenomena and to find surprising statistical properties of known ones.

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Harwit replies: Benjamin Monreal is quite right. Expanding data volumes have had an enormous impact on astronomical discovery. Although my article could not include it, my book *Cosmic Discovery* (Basic Books, 1981) provides a plot of the eight orders of magnitude improvement over the naked eye, in sensitivity and data gathering rates, made possible by 1980 through increased telescope apertures, more sensitive photo-response, and increasingly large numbers of spatial resolution elements on photographic plates and photoelectric arrays. The recent discovery, by the DENIS and 2MASS all-sky surveys, of a few dozen extremely low-mass brown dwarfs among hundreds of millions of more ordinary stars, shows the added value of machine data processing.

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Tevatron's Complex Collider Cousins

According to Bertram Schwarzschild's story "Disappointing Collider Performance and Tight Budgets Confront Fermilab With Tough Decisions" (PHYSICS TODAY, November 2003, page 22), "The Tevatron collider is, by far, the most complex accelerator ever to reach the operation stage." This is not so—other accelerators of comparable complexity exist, if complexity is measured by the technologies used, the numerical size of the accelerator subsystems, or the number of operational modes. A few examples from other hadron accelerators illustrate our point.

Antiprotons were also generated for CERN's SPS collider, which operated from 1981 to 1990. In addition, HERA, in operation at the German synchrotron facility DESY, is an electron–proton collider of comparable size and proton energy. Like the Tevatron, the HERA proton ring uses superconducting magnet technology.

In its brief career so far, Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) has collided not only polarized protons with fully stripped gold ions, but also deuterons with gold ions. Although RHIC's proton energy is only a fourth of the Tevatron's, the total length of its two rings of superconducting magnets exceeds the length of the Tevatron's single ring. RHIC has more magnets, more power supplies, and more RF cavities than the Tevatron.

Yes, the Tevatron is the premier collider at the energy frontier, but it is not alone in its complexity.

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Physics Curriculum Needs Fluid Mechanics

Thanks to Jerry Gollub for his wake-up call "Continuum Mechanics in Physics Education" (PHYSICS TODAY, December 2003, page 10). Ever since I made the switch from physics to MEMS (microelectromechanical systems), I've wondered why the only people I encounter who know how to do fluid mechanics were trained as mechanical engineers. Particularly in MEMS, where a real understanding of how to extend fluid dynamics knowledge to nontraditionally small scales is useful, a physicist's broad training would be a great advantage. Yet, when I go back to the physics camp and tell folks what a hot topic fluid dynamics is, with demand for systems that perform fluid mixing, DNA sensing, and chemical sensing on a single chip (the so-called lab on a chip, useful from drug development to emergency room care), I'm told that the standard four-year physics curriculum just doesn't allow time to fit in a course on fluid dynamics.

Clearly, engineering students have a great advantage in the job market because their education has focused on practical problems, with the curriculum continually adjusted to remain relevant to the working world. Anything that gives physics students a unique ability over students of other disciplines—for example, mastery of fluid dynamics—should be highly encouraged. Otherwise, the physics curriculum will continue to become less relevant, and students will continue to flock to disciplines that promise a better return, both in paycheck and in career choices, on the intense investment of effort in school.

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Green's Theorem in Stained Glass

I was glad to read Lawrie Challis and Fred Sheard's biographical essay "The Green of Green Functions" (PHYSICS TODAY, December 2003, page 41) about George Green, the underappreciated mathematician whose function is so widely used. In addition to the Nottingham and Westminster Abbey memorials described in the article, a memorial stained-glass window showing a diagram used for setting up calculations with Green's theorem adorns the dining hall at his Cambridge University college, Gonville & Caius. It was a colorful contribution to my mathematical pilgrimage to England a few years ago.

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