

Today many of us in astronomy look at the above two conceptual changes to the way we do science as normal, but actually they have produced a radical realignment in the way astronomy is done. For the large and, in the US, substantially federally funded telescopes, the science systems engineering approach is the most effective way to increase the science return on the very expensive facilities being built for scientists. The approach particularly recognizes that the original scientists and engineers who conceived of and built the facility do not have a lock on what science will get done, nor do they have unique insight on how best to undertake any given experiment. Through a peer review process, any astronomer can gain access to the facilities and use them in new and innovative ways.

More important, even, than facility access, the science systems engineering approach is a commitment to make calibrated and crucially trusted data accessible to anyone with an internet connection. In addition, adopting common standards across observatories, as the astronomy community has done, allows the combination and comparisons of astronomical data from different facilities, which in turn can lead to unanticipated discoveries. One example is the use of ground- and space-based telescopes that led to the discovery and confirmation of the accelerating universe, for which Saul Perlmutter, Brian Schmidt, and Adam Riess received the 2011 Nobel Prize in Physics.

Many people may well argue that the science systems engineering approach adds real costs to a project. When the sole scientific objective is to deliver a set of cosmological parameters, such as with the *Wilkinson Microwave Anisotropy Probe* (WMAP), that may be true, and the added expense may add little science value. Even the WMAP team, though, has released calibrated maps, and the original data, for others to reanalyze. However, if a planned facility is intended to have multifaceted exploration and discovery capabilities, certainly in astronomy it is now hard to imagine walking back from the model of broad access to trusted observational data archived under a common standard.

Thomas Friedman described in his book *The World Is Flat: A Brief History of the Twenty-First Century* (Farrar, Straus and Giroux, 2005) how commerce and entire industries are being radically changed because today anyone with an internet connection can, in principle,

participate and even compete with more established industries. He describes the world as being “flattened” by this enabled global access. In astronomy, we are creating a similar paradigm, where anyone with a good idea and an internet connection can get access to fully calibrated data taken with the *Hubble Space Telescope*.

The continued commitment to a “flattened” approach to large astronomy is not without its own issues, however. Over the decades, astronomy has become very much about data and less about machines, in the sense that astronomers have generally become more distanced from the hardware that is taking the data. As Giacconi noted in a 2013 commentary,² “Most of the results have been good, except for a separation between builders and users, which I believe is not healthy for the field.”

A second issue lies at the extreme of the science systems engineering model, with the enormous possibilities that will be opened up by the Large Synoptic Survey Telescope (LSST), which in the early 2020s will continually scan and image the sky. That facility will produce approximately a petabyte of archived, calibrated images every two months.³ As our new tradition demands, those data will be made available almost instantly to the entire community over the internet. According to Mario Juric, the LSST data management project scientist, that data stream will contain an estimated 2 million events per night, which could include, for example, a supernova, a gamma-ray burst, a flaring star, or a fast-moving near-Earth asteroid.

To enable the innovation and enormous scientific productivity that have characterized a community now accustomed to using large astronomy facilities, astronomers outside of the LSST science team will have to find a way to effectively filter the 2 million events into coherent individual projects. How to bring all astronomers into the new big-data era is the next challenge for the Giacconi model.

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Letters

Notes on the glass-forming ability of bulk metallic glasses

The article “Bulk metallic glasses” by Jan Schroers in the February 2013 issue of *PHYSICS TODAY* (page 32) was very enjoyable. The author’s remarks on the recent progress of bulk metallic glasses are much appreciated. However, the author made no mention of original work from Baixin Liu’s group at Tsinghua University in China. I offer this short note as a supplement to Schroers’s article.

Schroers concludes that one can describe a material’s glass-forming ability (GFA) as being either inversely proportional to its critical cooling rate or proportional to its critical casting thickness. Liu and coauthors argued that, more broadly, the GFA of a metal alloy system is quantitatively related to its glass-forming range.^{1,2} The GFR not only shows whether metallic glasses could be obtained in a system, it also indicates the alloy composition range within which metallic glasses could be formed by some specific glass-producing techniques. The wider the GFR, the greater the GFA of a metal system.

Indeed, Jia Hao Li and coworkers from Liu’s group have shown through computations and simulations based on the interatomic potentials of some 10 representative binary metal systems that each system has two critical solid solubilities that define the GFR: For the composition range bounded by the two values, metallic glass formation is energetically favored. The predicted GFRs from the interatomic potentials are well supported by the experimental observations.² A similar approach applied to some ternary metal systems that form bulk metallic glasses showed not only that the favored composition region (GFR) could be located, but also that an optimal composition, defined as the one having the maximum driving force for crystal-to-amorphous transition, could be pinpointed.³ I think the predicted optimized composition could be correlated to the maximum size of the metallic glass obtained by copper-mold casting with a specific cooling rate. If so, the physical and technical definitions of GFA could then be bridged.

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■ **Schroers replies:** In the section of my article that Jianbo Liu cites, I did not attempt to report correlations with glass-forming ability but simply to state how GFA is defined—namely, by the critical cooling rate, which also establishes a critical casting thickness.

In their work, the Tsinghua University researchers report a correlation with GFA and try to understand and predict why glasses form. Their work is based on an idea by Takeshi Egami and Yoshio Waseda.¹ The Tsinghua group essentially confirms the well-established Hume-Rothery rules—in particular, that for a specific size difference between two metallic atoms, only a limited range of compositions will form solid solutions.

I agree with Liu that destabilizing solid solutions is a requirement for glass formation, but it is at most a minimum one. However, predicting and quantifying GFA through identifying compositional limits of solid solutions is insufficient. Beyond those solution limits, mixtures often form intermetallic phases, homogeneous crystalline phases that compete with the glass in terms of stability. Moreover, intermetallics can be difficult to consider in molecular dynamics simulations that have been used by the Tsinghua group, depending on the simulations' assumptions. In summary, the Tsinghua group's finding is a requirement for glass formation; however, it is insufficient to predict glass-forming ability in a quantitative manner and is certainly not suited to act as a predictor for glass formation.

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Black-box electronics and passive learning

Ludwik Kowalski raises some interesting points on the nontransparent technological devices that pervade our lives (PHYSICS TODAY, October 2013,

page 8). I have an additional concern about those devices. I agree with Kowalski that they fail to promote curiosity. But suppose one of my electronic devices behaves in a way I don't expect. If I do somehow become curious about its behavior—Was it a network glitch? Design whim? Virus?—what I might learn has nothing to do with science or causality. I'm more likely to learn about human nature, corporate look and feel, or perhaps that what I observed was just a random event I cannot duplicate. What I learn will lead me away from science—from even thinking that science could be relevant for understanding my world.

On the engineering side, if I want to fix or improve my device, I can't; the hardware is typically sealed. Software presents a similar situation; writing for devices requires advanced skills from the outset and possibly a license agreement. My curiosity is far from encouraged. The lesson to me is, "Sorry, technology is beyond your grasp."

I think most modern devices not only fail to promote curiosity, they actively discourage it. I find it ironic that our wealth of technology, distributed widely in the population, may end up contributing to an antiscience mindset. That could bode ill for public debate on, say, climate change.

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■ **The lack of transparency** of our new electronic gadgets, Ludwik Kowalski wrote, is an advantage in efficiency, but it also carries potential harm. While I agree, I suggest that the harm could largely be avoided by novel teaching methods and new ways of writing high school textbooks.

What can we do to raise our technological gadgets above the level of black boxes—or black holes that swallow any student involvement? To appropriately connect modern technological tools to the important principles and laws of nature, we need to teach science, technology, engineering, and mathematics (STEM) as a whole, based on unifying principles. That approach should not only remedy some of the problems that Kowalski mentions but also help us to resolve the lingering problems of STEM education altogether. In fact, if I were asked to formulate the educational problems of STEM in one sentence, I would say, "It's the textbooks."

I was confronted with the problems of STEM education in 2007, when I was serving on the National Science Board.



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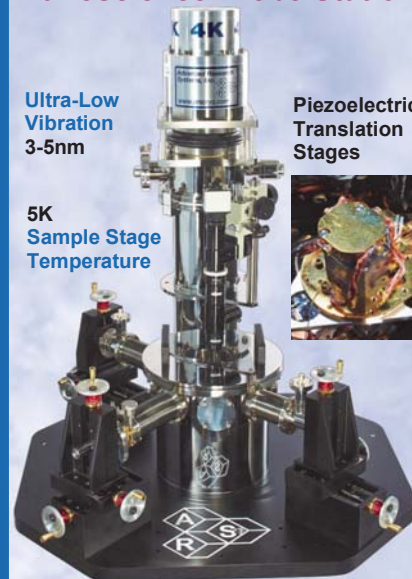
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