still include capabilities at the scientific forefront. Far from business as usual, Astro2020 does not forward a ranked list of missions; rather, it imagines the Great Observatories Mission and Technology Maturation Program to study multiple mission concepts in the same decade. Individual mission cost targets would be appropriate for the scientific scope. While the survey prioritizes the first mission to enter the maturation program, it emphasizes that multiple missions should be studied this decade, so that if the one at the top of the list runs into problems, delays, or large cost overruns, backup options are ready.

First in the list of missions to be matured is an observatory that spans the wavelength range covered by the *Hubble Space Telescope* (which is 2.4 m in diameter and covers UV to near-IR) and has the collecting area of the *JWST* (6.5 m in diameter but mainly IR). The large IR/optical/UV (IR/O/UV) mission would have the ability to image a target planet while blocking out the light of its parent star, even when the star is 10 billion times brighter than the planet. It is an ambitious mission, on the scale of the *JWST*, yet the survey sets a target that it should not cost significantly more than the *JWST*.

The choice is motivated by the mission's ability to diagnose the atmospheres of planets outside the Milky Way to search for signatures of life—which, if detected, would change the way humans view their place in the universe. Like *Hubble*, the IR/O/UV mission would revolutionize our understanding of galaxies and stars and of the interstellar, circumgalactic, and intergalactic gases that give birth to them and would link them in a complex cosmic ecosystem. The IR/O/UV mission is technically challenging, and like the *JWST* and *Hubble* before it, it demands a major investment; NASA is the only agency worldwide capable of leading it.

Also compelling—and essential to advancing modern astrophysics—are a next-generation x-ray telescope and a mission sensitive in the far-IR. The former, with resolution matching that of NASA's *Chandra X-Ray Observatory* but with a vastly greater collecting area, would map hot, diffuse structures that are believed to feed the growth of galaxies and would peer back to find black holes forming in the early universe. The latter would unveil the dense regions of gas and dust enshrouding sites of star formation and the active central regions of many galaxies, and it would reveal the complex chemical processes that give rise to stars, planets, and ultimately life. With disciplined study and technology development, both missions can realize transformative capabilities on a size scale only one-third that of the large IR/O/UV mission. With strategic investment in the coming decade, both could also be ready to launch in quick succession.

Our "crystal ball" description of future missions and observatories beyond the *JWST* has focused on the largest space missions, but Astro2020 also recommends that NASA continue with a balanced portfolio of mission sizes from the large missions or Great Observatories described here down to probe, explorer, and smaller missions. Our committee was only tasked with planning future US-based activities, but in reality many of the projects will involve international partnerships, and implementation of the NASA road map will need to take into consideration missions led by the European Space Agency and other countries.

Astro2020 envisions a bright future, with eyes on the universe spanning the electromagnetic spectrum.

**Fiona Harrison**
*(fiona@srl.caltech.edu)*
*California Institute of Technology*
*Pasadena*

**Robert Kennicutt**
*(rck@arizona.edu)*
*University of Arizona*
*Tucson*
*Texas A&M University*
*College Station*

LETTERS

# STEM volunteers

In response to Toni Feder's item "The US is in dire need of STEM teachers" (March 2022, page 25), I would like to make note of the work being done by the American Association for the Advancement of Science's STEM Volunteer Program (stemvolunteers.org), which I coordinate. We recruit STEM (science, technology, engineering, and mathematics) professionals to assist K–12 teachers in their classrooms.

The program began in 2004 and currently has 110 volunteers in four school districts in the Washington, DC, metropolitan area. Our retired volunteers commit to a few hours one day a week in the classroom for the school year. Those still working commit to a few hours every two to three weeks. Many volunteers exceed those commitments.

Volunteers help students learn subject matter through projects rather than by rote. They also present on technical subjects in the curriculum and organize "Ask a Scientist" sessions, in which they answer questions from groups of students.

One teacher wrote an email to a volunteer thanking him for the gift of his time and stating that it was an "absolute pleasure" to work with him. "You make science come alive for our children and I am very grateful," she wrote. "I will do all I can to encourage more schools to use the program and get visiting scientists."

Prospective volunteers are contacted through a variety of mechanisms—such as through societies' local sections, newsletters, the DC MIT Club, and retirement associations. The American Physical Society has supported the program from the beginning, including annually sending recruiting notices to its members in the DC metropolitan area.

I am convinced that a national program can be designed to produce a significant increase in the number of volunteers from the large number of STEM graduates. As of 2019, there were 12.3 million college graduates whose highest degree was in a science or engineering field, according to NSF's National Survey of College Graduates. A consortium of STEM societies is the best approach for implementing a program in support of K–12 STEM education.

Increasing the number of volunteers will not solve the teachers shortage, but volunteers can be a significant help, in particular with assisting teachers who have a limited background in STEM. And they can serve as substitute teachers, as several of our volunteers have done.

**Don Rea**
*(donaldrea@aol.com)*
*AAAS STEM Volunteer Program*
*Washington, DC*

# Mind and matter

Andrew Zangwill's March 2022 article (page 28) presents an insightful portrait of Philip Anderson in dynamic, human terms. I was particularly drawn in by Zangwill's mention of Anderson's Anglophilia and his association with leading researchers at the University of Cambridge. In that context, two of Anderson's "four facts"—that computers will not replace scientists and that good science has aesthetic qualities—resonate with Brian Josephson's interests in the past 20-odd years.

I met Josephson at an international conference, titled Home and the World: Rabindranath Tagore at the End of the Millennium, which was held by the University of Connecticut in September 1998. Josephson spoke about the poet-philosopher Tagore (1861–1941) and science.[1] From my relatively brief encounter with him, I understood at the time that Josephson was especially interested in the area of mind–matter interactions, and that, of course, had some relevance to the well-known 1930 conversation that Tagore had with Albert Einstein on reality and the human mind.[2] Mind–matter interactions have also been an area of sustained interest for many leading scientists, including Ilya Prigogine and Roger Penrose.

It is also quite noteworthy that Zangwill mentions Charles Kittel as one of Anderson's mentors at Bell Labs. Many of us pursuing physics and engineering in India in the 1970s were introduced to Kittel's classic textbook *Introduction to Solid State Physics*, which was foundational to our understanding of the subject.

## References

1. B. Josephson, in *Rabindranath Tagore: Universality and Tradition*, P. C. Hogan, L. Pandit, eds., Fairleigh Dickinson U. Press (2003), p. 107.
2. M. Popova, "When Einstein met Tagore: A remarkable meeting of minds on the edge of science and spirituality," *Marginalian* (27 April 2012).

**Monish R. Chatterjee**
*(mchatterjee1@udayton.edu)*
*University of Dayton*
*Dayton, Ohio*

# $CO_2$ air-capture costs

David Kramer's "A windfall for US carbon capture and storage" (January 2022, page 22) mentions the $3.5 billion appropriated by the US government for direct air capture. I would like to point out that the energy costs of capturing carbon dioxide already diluted in the atmosphere would be prohibitive.

Methods tried so far employ a reusable absorber cycled between absorption and emission, with an input of energy required at one or both parts of the cycle. The unavoidable energy requirement for a cycle can be calculated from the entropy change $\Delta S$ of the $CO_2$ going from its present atmospheric concentration of about 400 ppm to a concentration needed for disposal or use, say 1 atmosphere.

Per unit mass and at room temperature $T$, that energy would be $T\Delta S = RT/M \ln(10^6/400) = 4.4 \times 10^5$ kJ/ton (t), where $R$ is the molar gas constant and $M$ the molar mass. If you assume the energy is applied electrically, and at a present US price of 12¢/kWh, the energy cost is \$15/t. So far there are no reports of technologies that are anywhere close to that energy requirement or cost.

Earth's atmosphere weighs $5.2 \times 10^{15}$ t. The unavoidable entropy cost to remove just 1 ppm (by volume) of $CO_2$, or $7.9 \times 10^9$ t, would be \$120 billion. After recovery at 1 atmosphere, there are the added costs of disposal, which is complicated by the residual atmospheric gases in the recovered $CO_2$.

The cost could be reduced if the energy is somehow supplied directly rather than after conversion to electricity. But no energy source is free because its energy could otherwise be converted to electricity and sold.

The costs of mineralization are more difficult to estimate. The absorber is used only once, not cycled. Costs might include those for accessing, processing by crushing and dispersing, and gathering and disposing of the absorber.

**John Tanner**
*(pust@datawav.net)*
*Idaho Falls, Idaho* PT