No matter where you retire, you will find a school district that needs substitute teachers for STEM classes. If you were a physicist for 40 years, you'll find that you have plenty of material to inject into almost any class. No larger organization is required!

Reference

1. S. L. Garrett, *Acoustics Today*, Fall 2023, p. 69.
2. US Census Bureau, "QuickFacts: Salinas city, California," https://www.census.gov/quickfacts/fact/table/salinascitycalifornia.

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CO_2 pipelines: A way forward?

David Kramer's piece "Capture alone isn't sufficient to bottle up carbon dioxide" (Physics Today, July 2023, page 22) focuses on the need in the US to create a massive CO_2 sequestration capacity, which is indeed in need of attention. But the story was deficient in one respect and inaccurate in another.

In Oklahoma, induced earthquakes over the past decade have mainly been attributed to wastewater disposal—in particular, high injection rates—but some have been associated with hydraulic fracturing, or "fracking."[1,2] Those relationships suggest that high-rate injection of supercritical CO_2 into deep saline aquifers may lead to seismicity. Indeed, the Intergovernmental Panel on Climate Change foresaw that possibility in 2005.[3] Because the physical properties of supercritical CO_2 differ from those of wastewater, it's uncertain whether they will have identical seismogenic effects. But there is a need for regulations, guided by independent research, that ensure that CO_2 sequestration is performed in a manner that does not lead to earthquakes.

Carbon dioxide is heavier than air, and therefore its airborne dispersion characteristics are altogether different from those of natural gas, and CO_2 presents an increased danger to both land-based and aquatic life. Indeed, contrary to Kramer's assertion that no one was injured in the 2020 CO_2 pipeline rupture near Satartia, Mississippi, the event led to the hospitalization of at least 45 people in addition to the evacuation of over 200.[4]

Given that risk, the environmental hazards, and the potential for violating the rights of Indigenous communities, CO_2 pipelines have unsurprisingly been met with public opposition. The carbon capture and sequestration community should respond by building trust with the public—starting with repurposing existing natural gas pipelines to transport CO_2—and by strictly adhering to environmental protection regulations, treaties with Indigenous communities, and existing legal requirements. Rules and regulations must be changed to ensure that the characteristics of CO_2 are fully accounted for, both in its transportation and in its sequestration, and not to accelerate the laying of new pipelines.

References

1. M. Weingarten et al., *Science* **348**, 1336 (2015).
2. R. J. Skoumal et al., *J. Geophys. Res. Solid Earth* **123**, 10918 (2018).
3. Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage*, B. Mertz et al., eds., Cambridge U. Press (2005), p. 249.
4. J. Simon, "The U.S. is expanding CO_2 pipelines. One poisoned town wants you to know its story," NPR, 21 May 2023, updated 25 September 2023.

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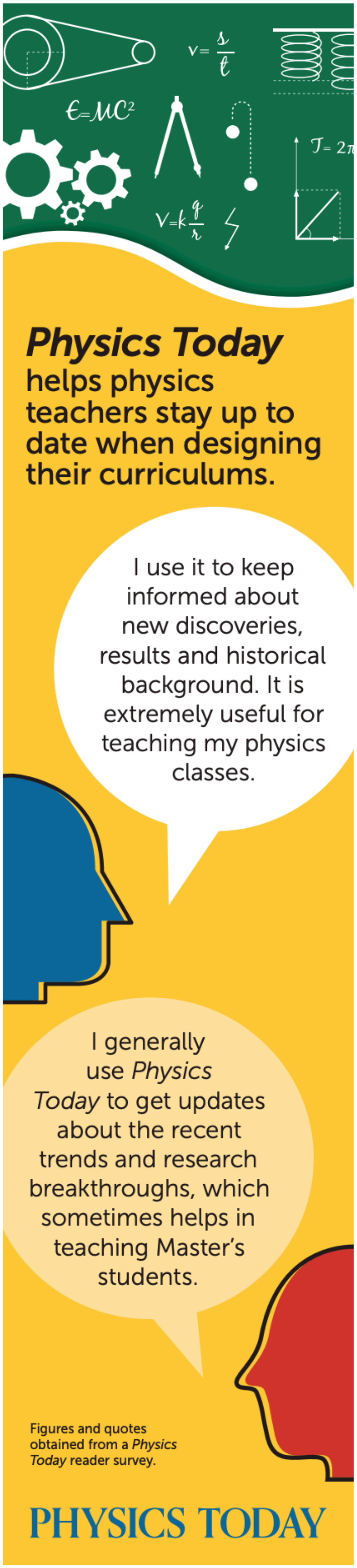
A fulfilling career

I admired how the obituary of Benjamin Breneman Snavely (Physics Today, October 2023, page 69) shines a light not just on his research accomplishments but also on his life of service in the private and public sectors. I did not know Snavely, but I am grateful for how my life has been touched by many scientists like him. The authors' remembrance shows how a career in physics offers us—beyond moments of breathtaking joy in a new discovery—a path toward sustained happiness while we help those around us live enriched and fulfilling lives as we engage in our



pursuit of expanding the frontiers of knowledge.

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Earth's radiative balance

In the July 2022 issue of PHYSICS TODAY, Martin Singh and Morgan O'Neill address the thermodynamics of Earth's climate system (page 30). Their statement that "the climate system is close to an energy balance at all times" is true, but only if energy has been redistributed by Earth's fluid systems, oceans, and atmosphere. Their following sentence, which states that "terrestrial radiation is emitted to space at approximately the same rate at which solar energy is absorbed," is ambiguous and does not apply locally or instantaneously.

The radiant heat balance of the atmosphere, oceans, and surface of the planet depends on Earth's absorption of short-wave radiation from the Sun, long-wave emissions into space, and reflections of short-wave radiation from Earth's surface and atmosphere.

The atmosphere absorbs less than 20% of incident solar beams. Reflection and scattering from the atmosphere and Earth's surface cause 30% of the solar beams to be lost to space. The remaining 50% of the Sun's energy is unequally distributed across the planet's surface. Between the latitudes of 40° N and 40° S, more energy is received annually from the Sun than is lost to space. Poleward of those latitudes, more energy is lost to space than received from the Sun. If that imbalance were not redressed by heat transported by the atmosphere and oceans, the high latitudes would turn into a block of ice and the tropical latitudes would become unsustainably hot.[1]

For the polar regions of heat deficit to be redressed, they must draw on the tropical regions of excess heat. Approximately 30% of the excess is transferred from the tropics to the polar regions by the oceans.[2] The remaining 70% must be transferred to the poles by the atmosphere to achieve the climatic equilibriums of Earth's temperatures. Surface winds in the tropical regions of excess heat, however, are directed toward the regions of excess. Heat transport from the "warm" tropics must therefore occur at altitude rather than at the surface.

In considering the vertical motion of hot, moist tropical air, a useful, adiabatically conserved quantity is the equivalent potential temperature, which can be defined as the temperature that a parcel of air would have if all water were condensed at constant pressure and the entropy released from the sample to heat the atmosphere.[3]

A midtropospheric minimum in the vertical profile of the equivalent potential temperature prevents simple mixing from transferring surface heat to the upper levels of the troposphere. To affect that transport, protected vertical transport channels, referred to as hot towers,[2] penetrate the midtropospheric temperature minimum, and the various components of the atmospheric general circulation allow energy to reach the polar region's upper troposphere.[4]

The set of thermodynamic interactions between Earth and the Sun can be explained in quantitative detail. In fact, the complex of scales of motion that governs the radiative relationships is manifested in Earth's climate. Besides climate issues, researchers have only recently begun studying those various scales for their use by birds and perhaps other animals.[5] Cause and effect of such factors challenge predictability.

References

1. M. Garstang, D. R. Fitzjarrald, *Observations of Surface to Atmosphere Interactions in the Tropics*, Oxford U. Press (1999).
2. J. S. Malkus, in *The Sea: Ideas and Observations on Progress in the Study of the Seas*, vol. 1, M. N. Hill, ed., Interscience (1962), chap. 4.
3. American Meteorological Society, "Glossary of Meteorology," https://glossary.ametsoc.org.
4. J. H. Jiang et al., *J. Geophys. Res.* **109**, D03111 (2004).
5. M. Garstang et al., *Animals* **12**, 1470 (2022).

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