Fusion breeding for sustainable carbon-free power

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have to be a genius to be successful."

In contrast, Peter Hansen asserts that there are indeed math-brained people and non-math-brained people. When we see some introductory students "get it" quickly and others struggle, it's easy to have such thoughts. But we don't typically see the history or opportunities for learning that may have led to those differences. Moreover, the beliefs and expectations that children get from their parents and teachers are well known to have a powerful impact on their behavior and success. The belief that a child is inherently poor at math is very likely to be a self-fulfilling prophecy. We discussed the extensive studies showing that when students learn to believe that working on challenging material helps the brain grow, their learning and performance in math and science improve, sometimes dramatically. The effects are often greatest for students with a history of underperformance.

Aaron Slepkov astutely notes in the value-affirmation intervention shown in our figure 3a and reference 11, there was a negative effect for men on one outcome (exam scores). Due to a lack of space, we were unable to include a discussion about what appears to be a statistical anomaly. That pattern did not replicate on other outcomes (Force and Motion Conceptual Evaluation scores, course grades) or on any outcome in a replication study.[1] That result is reassuring; nonetheless, it is essential to monitor effective interventions for potential adverse effects among subpopulations of students.

The lack of impact on males is consistent with the broader literature we listed on value-affirmation and other interventions that mitigate the threat associated with negative stereotypes—for example, social-belonging and wise-feedback interventions. Members of minority or at-risk groups in school settings generally show benefits from those interventions; members of majority groups are usually unaffected but in some cases also benefit. This is not surprising, as the interventions are carefully targeted to the specific barriers faced by students in settings where their group is underrepresented and faces negative stereotypes.

Sadri Hassani raises many points without supporting data; we disagree with most of them, and believe that many people would find them offensive. However, there is some truth to his claim that what matters ultimately is, "How much time are they willing—or forced—to spend, at an early age, practicing physics and the mathematics that goes with it?" There is no doubt that mastering complex material takes time. But what motivates a person to invest that time, to struggle through challenges? If a student has a fixed mindset of "I just can't get physics" or "Maybe people like me don't belong" then he or she is less likely to invest in the field. The purpose of remedying psychological barriers is to encourage students to invest in physics.

Where will growth in physics come from in the coming decades? The greatest opportunity for growth comes from groups that are underrepresented in the field, like women and minorities.

Our article discussed the barriers to success that well-qualified women and ethnic-minority students encounter in the physics classroom. The research we reviewed suggests that simple and low-cost exercises can make a significant difference in bringing these people into the field.

Reference

1. L. E. Kost-Smith et al., in *2011 Physics Education Research Conference*, AIP Conf. Proc. vol. 1413, AIP (2012), p. 231.

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Any reasonable option for midcentury, sustainable, carbon-free power should be given serious attention. In an earlier letter to PHYSICS TODAY (May 2012, page 12), I suggested one—fusion breeding—as a better option for the US fusion program. The June 2014 issue of the magazine had three articles on the dilemma: "Pulsed-power machine studies weapons, simulates stars" (page 24), "Turmoil at ITER continues" (page 26), and "Nuclear energy output slows as climate warms" (page 28). However, the problem is much worse than those articles imply. Two energy options that have received considerable attention—controlled fusion and "green energy" (solar photovoltaic, solar thermal, wind, and ethanol)—are currently encountering fierce headwinds.

Consider the following: The cost of ITER has grown considerably and its completion date has been dramatically extended. Tokamaks will probably never be economical stand-alone pure fusion reactors, but they could be fusion breeders. The National Ignition Facility has missed its gain milestone by about three orders of magnitude. And recently the US Congress has taken a hard and unsympathetic look at fusion.

Meanwhile, green energy is not living up to its promise. According to a speech by German vice chancellor Sigmar Gabriel to his nation's solar industry leaders in April 2014, the collapse of that country's green-energy infrastructure seems imminent, and Germany's use of soft coal has significantly increased, which in turn has raised greenhouse gas emissions and electricity prices. In fact, any computer search will show that coal use has greatly increased worldwide in the past decade.

Although there are no guarantees that pure fusion and green energy will continue to fail or that coal use will continue its rapid increase, most indications are discouraging. Hence it seems appropriate to pay more attention to another option for sustainable, carbon-free midcentury power: fusion breeding.

A fusion breeder can fuel many thermal nuclear reactors of equal power. It takes two fast-neutron fission reactors at maximum breeding rate to fuel a single thermal nuclear reactor. (A single fast neutron reactor, however, can be configured to burn the actinide waste products—principally plutonium—of many thermal nuclear reactors of equal power.)

Developing fusion breeding will take decades of dedicated effort, but it is much more achievable than pure fusion. In any case, fuel for fission reactors is currently available and will be for a few decades. The time to develop fusion breeding and the time to largely deplete conventional nuclear fuel could well match up. A review article[1] and a textbook chapter[2] offer more details regarding the plasma physics and nuclear aspects of fusion breeding. It might well be that fusion breeding could develop into a sustainable, carbon-free power source by midcentury.

References

1. W. Manheimer, *J. Fusion Energy* **33**, 199 (2014).
2. R. Moir, W. Manheimer, in *Magnetic Fusion Technology*, T. Dolan, ed., Springer (2013), chap. 14.

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