Nobel Laureate Carl Wieman: Effective Teaching Should Create Students Who Think Like Scientists

Teaching science and mathematics needs to be more of a science like astronomy, not a folk art like astrology as has been the case for too long, Nobel laureate Carl Wieman said at a national conference on strategies to build a stronger corps of science teachers.

The goal should be to have “all students think about and use science, mathematics, and engineering more like scientists do,” Wieman said. “The most valuable metric” for evaluating effective teaching should be creating patterns of scientific thinking.

Changing this orientation can have a dramatic impact on science, technology, engineering, and mathematics (STEM) education, said Wieman, the former associate director for science in the White House Office of Science and Technology.

He delivered the opening plenary address of the Seventh Annual National Science Foundation Robert Noyce Teacher Scholarship Program Conference. AAAS, which has collaborated with NSF on the program for five years, organized the invitation-only meeting. It drew more than 600 program participants from over 225 colleges and universities to Washington, D.C. from 23-25 May.

Wieman sketched out research findings over the last few decades from the fields of cognitive psychology, brain research, and the college science classroom that are yielding “a clearer picture about what is important for achieving learning, particularly of complex expertise like math and science.

“Good teaching is facilitating that learning,” he concluded. “The goal should be to have people come to think more like expert scientists.”

Wieman departed from his position in the White House office on 2 June, after serving as associate director since September 2010.

Elements of Expertise

Certain consistent features characterize expertise and how it is learned, regardless of the discipline. One is extensive factual knowledge of the subject area.

The second, according to Wieman, is a mental framework for organizing that knowledge so that it can be effectively retrieved and applied to solve problems.

“Third is the ability to monitor one’s own thinking and learning in the areas of expertise,” he said. It includes “self-checking or sense-making, of examining one’s thinking and coming up with ways to check if their answers make sense.”

Mastering a subject requires the learner to engage in “challenging but doable tasks or questions. It has got to be so hard that they have to put the full focus and effort into it; if they do that, they
can make progress,” Wieman said. “It cannot be impossible, but doing things that are easy, over and over again, has very little benefit.”

“There also has to be an element of feedback and reflection, both internal reflection...and feedback from the expert coach or teacher that gives them guidance for further improvement,” he suggested. “After doing this over and over for about 10,000 hours, you get to a world-class level of expertise.”

This intense repetition is necessary because learning in the brain “is much more like a muscle than we used to think,” he said. Both organs are built up through repeated strenuous challenges and the body’s response with physical remodeling.

**Reducing the Demands on Memory**

“Memory is not talked about much in education, but it is critically important,” Wieman said, and the limited discussion that does occur focuses primarily on long-term memory while short-term working memory is ignored.

He compared the latter to a personal computer with limited RAM. “The more it is called upon to do, to remember, the harder it is to process. The average human brain [working memory] has a limit of five to six new items, it can’t handle anything more.”

A new item is anything that is not in the learner’s long-term memory, he continued. “Anything you can do to reduce unnecessary demands on working memory will improve learning.”

Among them is elimination of unnecessary jargon. Wieman asked: “That new jargon term that is so convenient to you, is it really worth using up 20% of the mental processing capacity of the students for that class period?” Demands of working memory can also be reduced by shifting some learning tasks, particularly transfer of simple information from the classroom to pre-reading assignments and homework.

Using figures rather than verbal descriptions can reduce the demand on working memory. Analogies also work, he said, as they “take a complex relationship that is in the learner’s long-term memory already, and they map this new complex relationship on to it. So it takes up dramatically less capacity of working memory.”

Long-term retention, Wieman said, is based upon having the learner “retrieve and apply the information repeatedly, spaced out in time. It also has to be done cumulatively.

“Within memory, new material interferes and inhibits access to old material,” he said. “You really have to keep testing them on both old and new so they sort out that interference as you go along.”

**Teachers as Cognitive Coaches**
Wieman said these discoveries change how we think about the role of the teacher. A teacher is not simply “a dispenser of information,” he said, but rather “a cognitive coach.” Teachers need to transmit both the framework of expert ways of thinking and then “motivate the learner to put in the very intense effort required to actually do learning.”

A good teacher also provides specific, timely feedback to guide the learner’s thinking, Wieman noted. “That means recognizing and addressing particular difficulties—when they are using inappropriate mental models—and how to assist them to understand the changes that they need to make.”

Motivation will depend upon the prior experience, sociocultural background, and other environmental factors that have shaped the individual learner, but a few consistent features have emerged from the research literature.

One is that the subject or issue must be relevant, interesting, or useful to the learner. That is most easily achieved by tying it to something the learner already knows and values by putting it in a meaningful context. The learner must also have a sense that he or she can master the subject, “and perhaps even more importantly, how to go about mastering the subject,” Wieman said.

“A sense of personal control or choice in the learning process” also is a motivating factor, he said. “Giving them even a little tiny bit of control makes a big difference in motivation and outcomes.”

He criticized much of STEM homework assignments for giving “only the information necessary to solve the particular question.” Learners are not asked to sort through a forest of information to identify those pieces that are relevant to the question. “That is neglecting an absolutely essential component of expertise.”

Wieman presented data from an experiment with an experienced and well-regarded traditional university lecturer, and a post-doc trained to utilize these most recently identified concepts in expertise and memory. “The amount of learning was profoundly different” in the latter group, he said.

In the long run, for Wieman, “the core principle that you can’t get away from is that STEM education really lives or dies on the quality of the teachers in the classrooms.”

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