Summary written by Susan Millar

After being introduced by UW-Madison Provost Paul DeLuca, and OSTP Senior Policy Analyst Constance Steinkuehler, Carl Wieman (CW) stated that in this lecture he would focus on the question of how to apply research-based knowledge about how learning works to improving learning in college STEM courses. This topic directly relates to his larger education goal, which is to change STEM courses so that they result in more students who learn to think like scientists. He noted that this issue is of ever-increasing importance in the USA due to the growing importance of having a scientifically literate public in order to foster effective policies and a stronger economy. CW said he is optimistic about achieving this goal because emerging results from cognitive psychology, brain research, and education research on college STEM classes consistently point to a coherent set of principles and practices.

CW briefly described his own background as an educator. He began like most other faculty, believing that what is needed is to clearly explain the material to students, and then, for the many students who don’t get it, to either tell them again louder, or let them go. Over time, he realized that despite his best efforts doing this, most of his, and his colleagues', undergrad students did not leave their courses better able to think like scientists. He also noticed that essentially all his incoming grad students were clueless about how to do physics research when they arrived, yet functioned as good physicists within a couple years. Intrigued by this puzzle, he began his own study of research on learning and eventually experimental research on undergrad learning, with the aim of getting students to think like scientists. This led him to realize that an effective learning system was in place for the grad students, and that a more effective system for undergrads could be developed.

CW explained that he would proceed to present some relevant research findings on learning and then describe some ways to apply these findings to STEM classrooms.

Research on the nature of expertise shows that experts in a particular area have, with respect to that area:

- Factual knowledge of the area;
- A mental organizational framework that enables them to very rapidly and effectively retrieve and apply their knowledge, recognize and apply complex patterns, relationships, and concepts;
- Ability to monitor their own thinking and learning processes.

To develop world-class expertise in any area requires changing the brain (developing and connecting neurons in new ways) - the “10,000 hours” of intensive practice. The brain is closer to a muscle than we previously realized, and, accordingly, development of expertise requires:

1. Engagement in serious “brain exercise”: challenging-yet-doable tasks/questions that explicitly focus on the kind of expert-like thinking to be achieved. For example, for STEM, such problems force the learner to figure out how to develop specific mental models, be able to recognize what information in a situation is/is not relevant, and be able to self-check. However, in the typical STEM classroom, some of these needed elements are missing: e.g., typically students are presented with all the relevant and no irrelevant information, so they get no practice in identifying what is/is not relevant. (Reference: A. Ericsson’s research on “deliberate practice,” – see the popularized but accurate summary in Colvin’s book called Talent Is Over-rated.)
2. Teachers who function as “cognitive coaches” who:
   - Design practice tasks that foster expert thinking;
   - Motivate learning to provide LOTs of effort;
   - Provide timely specific feedback to guide learners’ thinking and learning, such as identifying and correcting use of inappropriate mental models.

So how to apply these findings in even the hardest classroom environment – the large intro lecture?

One approach is to use a targeted pre-class reading assignment with a brief online quiz, and then in class use a carefully-designed conceptual problem, with multiple choice responses that include attractive distractor responses. After students use e-clickers to vote individually on their answer, the students talk in small consensus groups (during which they explain reasons for saying which answers are correct and incorrect and get diverse feedback from other students) while the instructor listens in to identify students’ correct and incorrect reasoning. Then there is whole class discussion during which the instructor, guided by the questions/issues heard while the students worked in small groups, draws out for consideration all student reasoning. Then the instructor presents answers, using a demo or simulation. This is typically followed by numerous follow-up questions and discussion by students as they test, extend, and refine their mental models. To teach this way effectively requires much more content knowledge than lecturing (which can be an issue in K-12 teaching) and is much more fun for the instructors, because this process generates much richer responses from students, and enables instructors to react to the questions and puzzles that students actually have. Students learn more because they are being actively forced to develop/refine their mental models to become more like experts.

CW emphasized that this particular teaching approach, labeled “deliberate practice,” applies the research-based processes that cognitive psychologists have identified as required for developing expertise. Active learning approaches described in educational research, with names like active learning, real-world problems, and collaborative learning, also are based on many of the same elements of cognitive activity and effective feedback.

CW said that there are nearly 1,000 academic papers presenting research on the outcomes of these innovative methods for teaching undergraduate STEM. For example, consider the Force Concept Inventory (FCI), designed to identify conceptual mastery of the principles of force taught in 1st semester college physics courses. The FCI is used in courses on a pre-post basis. Findings from scores of courses at very different types of institutions (from Harvard to community college) show a huge difference in student performance outcomes depending on whether the standard lecture approach is used (~30% increase in right answers at end of intro physics course), or active learning approach is used (~60% increase in right answers). There are similar findings in other STEM fields. In a related study of conceptual mastery, researchers at Cal Poly collected data for many different faculty and showed that when they changed their teaching methods, the students’ learning greatly increased for all of the faculty members (see Hoellwarth and Moelter, Am. J. Physics, May 2011). CW then presented a study in which student outcomes for an intro class taught by a postdoc trained in his cognitive coach approach were compared with outcomes for students taught by a highly-regarded experienced lecturer, showing profoundly better outcomes (for all types of students) for the trained postdocs’ students. What is the primary factor that explains these findings? That students are engaged in more intensive mental activity, not that instructors are more or less good at lecturing. CW believes that findings like these should be compelling to university faculty and administrators.
CW then turned to a related topic: perceptions about science. He introduced this topic by identifying key differences in novice and expert perceptions of science:

- **Novice view**: physics content comprises isolated bits of information to be memorized, is unrelated to real life and handed down by an authority, and problem-solving is about pattern matching to memorized recipes (only useful for passing currently standard physics tests);
- **Expert view**: physics content comprises a coherent structure of concepts, describes the real world and is established by experiment, and problem-solving entails systematic concept-based strategies that can be applied widely.

His group at the U of CO developed a 7-minute course pre-post survey to identify change in perceptions about science. [The name of this survey is Colorado Learning Attitudes about Science Survey, or CLASS. See colorado.edu/seti/class/.] Findings from this survey: as a result of intro science courses, students generally become more novice-like in their perceptions about science. That is, CW explained, with regard to perceptions about science, we are doing not an ineffective, but rather an “anti-effective,” job of teaching intro STEM courses. He observed that this is a profoundly disturbing outcome, particularly in light of the need for public literacy about science and concern about the anti-science orientation of some of the US public. Moreover, he explained that Perkins at U of CO has also found that a student’s score on the 7-minute CLASS survey is a better predictor than 1st year physics course grades of which students will become successful physics majors. (During the Q&A, most people asked for more information about the outcomes of the perceptions of science survey. For example, in response to one questioner, he explained that the CLASS is likely a good predictor of which 1st-year students will succeed as majors because students who enter with expert-like learning attitudes toward science tend not be influenced by the negative effects of intro STEM courses and other factors.) These findings about attitudes toward science learning have spawned a lot of recent research, including that the use of active learning methods alone does not necessarily result in greater improvements in scores on the perceptions about science survey, and that there are a few specific instructional approaches (e.g., explicit presentation of the process of science, particularly the use of modeling) that have been shown in research studies to positively impact attitude outcomes.

CW encouraged faculty, administrators, and students to adopt a scientific approach to teaching and learning by applying research findings that have been shown to be broadly important. These findings include the importance of motivating learners, connecting with and addressing students’ prior thinking (areas where the diversity of learners’ prior experiences play an important role), and generally using methods that foster the changes in the brain needed to help people achieve expertise.

He also noted two reasons why he believes the national efforts to improve undergrad STEM learning have had weak results thus far: (1) because, as research studies show, we humans do not remember what it is we did not used to know, and thus instructors may find it very difficult to believe that just lecturing is not effective, and (2) because incentives for faculty to focus on improving teaching practices are weak, e.g., learning outcomes and teaching practices for individual faculty members are not effectively tracked, whereas research outcomes are tracked. He considers it a hopeful sign that university associations such as the AAU and STEM professional societies are beginning to focus on these issues of improving STEM undergraduate teaching, moving toward taking an “astronomy,” rather than an “astrology,” approach to STEM teaching.
CW concluded by presenting a short list of his favorite references (below), and taking questions.

- S. Ambrose et al., How Learning Works
- National Academy of Sciences Press: How People Learn
- Colvin, Talent Is Over-rated
- Wieman, Change Mag, Oct, 07 – carnegiefoundation.org/change/
- for simulations, see phet.colorado.edu
- for resources on effective clicker use, see cwsei.ubc.ca.