Good afternoon

Cognitive science, memorization, concepts, and chemistry

Presented At Chem Ed 2015,
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My Limited Scope:

• Students age 14 to Grad School
• Solving Well-Structured Problems
• In courses aimed at preparing students to be science majors.

My talk today is limited to addressing students before grad school, solving problems with clear right answers that prepare them to be science majors.
My name is rick nelson. I am co-author with Dr. Don Dahm of Rowan University of this textbook for preparatory chemistry published by W. W. Norton.
I write for the “Chemistry and Cognition” blog,
Was co-author with Don and Dr. Judy Hartman on this paper published last week in J Chem Ed,
But today I’d like to talk about this recent paper that I co-authored with Dr. JudithAnn Hartman who teaches chemistry at the Naval Academy. It will supply the detail and references for my slides and narration. I will post a link to the paper at the end of my slides.
What I am going to talk about is *new science*: findings that cognitive experts agree in 2015 are true, but 10 years ago, not all were convinced were true. Part of what we have learned is that the brain severely limits retention of new knowledge which does not fit into existing conceptual frameworks, so that most of what we talk about today will only "stick" if you review it later. Therefore, I will try to get you curious, and at the end I will give you a web address where you can review any slides of interest at a more reasonable pace whenever you like.
In First-Year Chemistry, who is asking for our help?
In General/AP Chem

Are students hoping to major in:

- Chemistry, Physics
- Biology, Biochem, BioTech
- Engineering, Geology
- Pre-Med, Vet, Dental, Optical, Pharmacy
- Medical Technology

Our mission in HS, AP, and general chemistry is to help students prepare, not for chemistry, but for science. NSF data tell us that in general/AP chem classes, there will be about 15 future science and engineering majors who graduate for every one chem major graduate. But chemistry plays a central role in all of these fields. When we help students go on to any of these careers, it's great for them, for us, and for America.
How Are We Doing?
Our work as instructors to help students become science majors has become increasingly difficult. NSF data tell us that the intent of students entering colleges to major in chemistry, physics, and engineering is as high as it ever been, but since 1966, the percentage of students graduating in chemistry is down about 60%. The decline in physics is about the same.
In the past ~30 years, the percentage of college students graduating as chem majors is down over 30%.
Might this be because students are instead majoring in Engineering (a mix of chem and physics) where there has been high demand?
No. General chem classes prepare 6 times more future engineers than chem majors, but since 1984, the percentage of students graduating in engineering has gone down 40%.
According to the President's Council of Advisors in Science and Technology, among students who initially state their intent to be chemistry and physics majors, dropout rates are close to 60%. For students hoping for careers in the sciences, for instructors, and for America, these are devastating results.
Here’s the good news.

The VERY Good News

• The Problem has NOT been Chem Instruction
• Science has found what went wrong
• Science has found how we can FIX the problem.
The evidence is that what went wrong is student background in math computation. Other science majors require first-year chemistry because when we teach chem, we also teach how to solve calculations that are required in all of the sciences --- that look like this with logs, exponents, and fractions,
Thus

\[ u_{\text{rms}} = \sqrt{\frac{3 \cdot \left( \frac{8.3145}{J \cdot \text{mol}} \right) (298 \text{K})}{4.00 \times 10^{-3} \frac{\text{kg}}{\text{mol}}} = \sqrt{1.86 \times 10^6 \frac{J}{\text{kg}}} \]

Since the units of J are kg \cdot m^2/s^2, this expression becomes

\[ \sqrt{1.86 \times 10^6 \frac{\text{kg} \cdot \text{m}^2}{\text{kg} \cdot \text{s}^2}} = 1.36 \times 10^3 \text{ m/s} \]

-- Zumdahl, 5th Ed. p. 218

Square roots, exponents, and fractions
In chemistry we teach equations, and how to correctly identify the data to put into an equation, as in the middle step above. But that middle step has 4 / marks: 4 fractions. Given the pace of general chemistry, textbooks often assume that students can go from the middle to the last step without help, as you see above - that in prior math, they have learned how to handle fractions. Is that assumption correct?
On our national test of math skills, the NAEP, in fractions, our 17-year olds went from 24% wrong in 1990 to 44% wrong in 1999.
\[ E = E^\circ_{\text{cell}} - \frac{0.0591}{n} \log(Q) \]

\[ = 1.76 - \frac{0.0591}{2} \log \left( \frac{[\text{Zn}^{2+}][\text{VO}^{2+}]^2}{[\text{VO}_2^+]^2[\text{H}^+]^4} \right) \]

\[ = 1.76 - \frac{0.0591}{2} \log \left( \frac{(1.0 \times 10^{-1})(1.0 \times 10^{-2})^2}{(2.0)^2(0.50)^4} \right) \]

\[ = 1.76 - \frac{0.0591}{2} \log (4 \times 10^{-5}) = 1.76 + 0.13 = 1.89 \text{ V} \]

-- Zumdahl, 5th edition

This is math computation.
\[
\text{Thus,} \\
\quad \quad u_{\text{rms}} = \sqrt{\frac{3}{4.00 \times 10^{-3}}} \frac{8.3145 \frac{J}{K \cdot \text{mol}}}{\frac{298 K}{\text{mol}}} = \sqrt{1.86 \times 10^6 \frac{J}{\text{kg}}} \\
\text{Since the units of } J \text{ are } \text{kg} \cdot \text{m}^2/\text{s}^2, \text{ this expression becomes} \\
\sqrt{1.86 \times 10^6 \frac{\text{kg} \cdot \text{m}^2}{\text{kg} \cdot \text{s}^2}} = 1.36 \times 10^3 \text{ m/s} \\
\]

-- Zumdahl, 5th Ed. p. 218

Computation.
Computation. But since 1990, student skills in computation have declined substantially.
Compare 1990 Iowa to 2002 in math computation.
In Virginia, by 2002, the state computation average fell to the abysmal 39th percentile (compared to a 1995 national average 50th percentile).

(Since 2002, most states have not reported computation data; see www.ChemReview.Net/BCCE2012Math.pdf )
In 2012, the OECD gave a test in numeracy (fundamental arithmetic skills) to adults in 22 nations. The red dots are the 16-24 year olds in each nation. Where are your students? Where? Dead last. Is it any wonder that our students have trouble in ....
Thus

\[ u_{\text{rms}} = \sqrt{\frac{3 \left( 8.3145 \frac{J}{K \cdot \text{mol}} \right) (298 \text{K})}{4.00 \times 10^{-3} \frac{\text{kg}}{\text{mol}}} \left( \frac{1}{1.86 \times 10^6 \frac{J}{\text{kg}}} \right)} \]

Since the units of J are kg \cdot m^2/s^2, this expression becomes

\[ \sqrt{1.86 \times 10^6 \frac{\text{kg} \cdot \text{m}^2}{\text{kg} \cdot \text{s}^2}} = 1.36 \times 10^3 \text{ m/s} \]

-- Zumdahl, 5th Ed. p. 218

Chemistry?
As instructors, our goal is to improve student success rates in science majors. To do so, we need to know: What went wrong in computation? The evidence is that problems grew as calculators were being used at earlier and earlier grades in schools, but that problems became especially acute after 1990.
Item analysis for fractions:
NAEP LTT, Age 17, 1978-1999

Note 1990 to 2002?
See 1990? What happened in 1990?
After the 1989 “Charlottesville Education Summit,” the US began a move from local K-12 education standards to “state standards.” By 1998, nearly every state had “state math standards” and tests on those standards.
The Math/Science Standards Debate

Do we tell students:
A. Memorize facts and algorithms?
   OR
B. Don't memorize, learn critical thinking, “think like a scientist,” and reason?

At that time, this question was being debated among curriculum policy-makers. Let me ask: In chemistry education journal articles and at conferences, which position do most speakers advocate: Approach A – or B? How many think speakers favor A? Favor B?
The Standards Debate

Do we tell students:

A. **Memorize** facts and algorithms?

    OR

B. Don’t memorize, learn critical thinking, “think like a scientist,” and **reason**?

Between 1990 and 2000, about 40 of the 50 US states adopted standards and textbooks that guessed B: that memorization should be discouraged and reasoning should be emphasized. This was a guess because in 1990, experts in how the brain works were not in consensus on how the brain solves problems.
You can see this impact. Virginia math standards told teachers to emphasize math reasoning. They did, and students did get better at reasoning.
About 40 of 50 states told teachers this. Take a look. Which grade?
3rd Grade

Not every state, but ~40 of 50

And what happened?
Item analysis for fractions: NAEP LTT, Age 17, 1978-1999

Nationally?
In Iowa
With standards told students “Don't memorize, reason,” computation skills fell apart. Virginia students learned to reason, and used calculators on state tests, but Computation, a key preparation for science majors, collapsed.
On the 2012 PIACC/OECD test, where calculators were allowed, for America: dead last. The "pro-reasoning, anti-memorization" state standards and the drop in computation skills occurred at the same time. That's a correlation. But were the standards a major factor causing the drop? Let's look at the evidence.
Since 1990, thanks to technology and increased computing power
Increasingly, we can watch the brain think. With the help of that technology, for about the past 10 years, nearly all cognitive scientists have been in agreement on the major elements of a model for how the human brain solves well-structured problems.
In that consensus model, the brain where you solve problems has two parts: Working memory and Long-Term Memory. What makes the human species unique is the enormous capacity of the Long-Term Memory (LTM) where we store knowledge.
LTM has a structure similar to a parallel processing computer.
LTM: Elements and Links

LTM is made up of small *elements* of knowledge *associated* with other elements. Those *linkages* describe its meaning of each element and the rules for its use. Those links *activate* in response to cues.

For example, if I make the sound “copper,” what associations come to mind?
All make up the “conceptual framework” for “copper” in your brain.
LTM is enormous: Over a billion small stored elements, including thousands of faces, places, names, dates, tastes, odors and sounds. Plus, most college educated adults can define from memory about 70,000 dictionary words. In speech, we effortlessly both choose correct words and apply complex rules for their use.
The goal of learning is to solve problems. The place the brain solves problems is in working memory (WM) by processing elements that have recently been read or heard – or activated in LTM. Everything activated in your LTM by a cue in a problem (such as “copper”) can be retrieved by WM to solve the problems.
The *Limit* on Reasoning:

During problem solving, **working memory** can hold and process

- ~All elements that can be recalled automatically from LTM.

Plus

- Up to **3-5** elements, each for **up to 30 seconds**, that *cannot* be fluently recalled from LTM.

But this is the speed limit of your brain. Take a look. Until 2001, we thought this 3-5 was about 7. Now we know -- it’s about 4. By 2005, these measurements were well-tested, verified scientific data.
WM can hold and process
• ~All elements recalled automatically, plus
• Up to 3-5 non-memorized elements.

Given ^ is true, is this true?

• Working memory is very limited when dealing with information that has not previously been memorized.

Vote: Yes? No?
**WM** can hold and process
- ~All elements recalled automatically, plus
- Up to 3-5 non-memorized elements for up to 30 seconds.

Given ^ is true, is this true?

- When solving chem problems, speed at recall matters.

Vote: Yes? No?

Is this true?
If your “novel” (new to you) WM is full, will this step during problem solving bump something out?

- Recall of $6 \times 7 =$ from memory: Y or N?
- Adding to WM the calculator answer to $6 \times 7 =$ : Y? N?

What was the policy of most states on times tables? As calculator use grew, mental math likely got rusty, but when states required early calculator use, the problem likely got worse.
WM can hold and process
• \(\sim\)All elements \textit{recalled automatically}, plus
• Up to 3-5 \textit{non-memorized} elements.

Given \(\sim\) is true, is this true?

• The more elements you move into LTM \textit{(memorize)} and \textit{link}, the more problems you can solve.

Vote: Yes? No?

How many would agree? Disagree?
Avoiding the Bottleneck:

• “[T]here are several ways to improve the functional capacity of working memory. The most central of these is the achievement of automaticity, that is, the fast, implicit, and automatic retrieval of a fact or a procedure from long-term memory.”


This is what the cognitive experts say. Take a look. What is central to getting around the bottleneck in WM? And what is automaticity? Those 5 leading scientists who study how the brain solves problems (and many other cognitive scientists) have written that they agree on this. Just as important, for the past 5 years, no cognitive experts have disagreed with what this says. When that happens, we have a scientific consensus.
They Add:

• “[t]o obtain the maximal benefits of automaticity…, facts and fundamental algorithms should be thoroughly mastered, and indeed, over-learned, rather than merely learned to a moderate degree of proficiency.

  -- (Geary et al., NMAP 2008)

“Overlearned” = ?

They go on to say this. Who knows what “overlearned” means? “Over-learned” means facts and algorithms are memorized until they can be recalled fast, perfectly, repeatedly. Even for instructors who have assumed a need for memorization in chemistry, the extent to which science says students need to memorize may be surprising.

Why is overlearning needed? LTM resists new information that does not “fit” in an existing conceptual framework. After ~age 12, it takes repeated and varied efforts to persuade LTM to hold on to new knowledge in unfamiliar fields.
Knowing automaticity plays a central role in problem solving, for instructors this becomes a key question.
This new book – by these scientific authors – by this semi-reputable publisher does a great job of explaining what students can do to …
To achieve automaticity:

**FIRST, practice retrieval:**
- Overlearn elements
- Distribute practice (the spacing effect)
- Self-test (clicker questions, flashcards, mnemonics)
- Quiz (*closed* notes) often
- Fade guidance (scaffold)

It says,
Then

Construct varied linkages that promote cued recall – using *active* learning:

- Demonstrations
- Guided inquiry
- Challenging problems
- Interleaved practice
- Reflection, elaboration

Instructors can help in building conceptual frameworks by engaging students in active learning.
Before you can build the linkages, an element must be moved into LTM ("memorized"). The brain accepts new information more easily if the associations are present, but that makes initial learning in a field especially difficult because the accepting framework is limited.
To find time to build automaticity, cognitive science recommends transferring a part of the delivery of lecture content to homework, so you have more time in class for active learning that builds links.
Why Textbook Reading Assignments Don’t Work

Summarize:
• When Sarwan and Chanderpaul were going on strongly, England were looking down the barrel. But they came back with Broad removing both of them within 8 overs of taking the 2nd new ball. It was always going to be difficult to survive with that kind of a batting line up and England then seemed to be on top. But the last pair hung around for ages to ensure that light is offered and they walk off.

Some of you might say: Why type up lecture notes? Why not have them read the text? Let’s see what that's like for students. Summarize this paragraph. Raise your hand when your summary is ready. Don’t all raise your hands at once. What’s the problem? Which words in this passage are difficult? Is the problem difficult words, or a framework with their associations? Comprehension studies say this is what a standard gen chem textbook looks like to most first-year students.
What does NOT work?

Inefficient at constructing LTM:

- Re-Reading
- Highlighting
- Cramming

*Make It Stick* documents that these strategies are a poor use of time devoted to study. Which strategies do your students tend to use?
Summary: Cog Experts Say

To solve problems,

• *First*, memorize needed facts and algorithms

• *Then*, reason with them; Apply in multiple contexts; space overlearning.

Goal: Automaticity in Cued Recall

The key principle is: Memorize, then reason.
If you tell students: “Don’t memorize. Reason,” what happens?
It was not anyone’s fault, but back in 1990, before technology came on line to help us study the brain, most states (and some science educators) guessed wrong on how the brain worked.
15 years ago, educators thought students could reason with what had NOT been memorized. Since then, science has discovered that the brain is limited almost exclusively to reasoning with what has been well memorized. How can we use this new knowledge to help students?
1. Tell students:

First memorize, then reason.

Three suggestions: First, explain to your students how learning works. Let them know they need to memorize, then apply, new facts and problem-solving procedures, Then memorize and apply again, repeatedly, to construct memory.
2. Design Instruction to Implement:

First memorize, then apply.

How can you do this?
Design:
• List facts and procedures needed in LTM
• Ask to see flashcards
• Scaffold problems-solving; supply worked-out answers
• Frequent short quizzes (closed notes)

Experts in cognition recommend these steps.
3. Require: Overlearn Pre-reqs First

- ID (esp. math) pre-reqs for a topic
- Quiz to assess automaticity
- If needed, overlearn and re-quiz

In chemistry, automating math before teaching "math with units attached" is especially important. Because of state standards that de-emphasized computation, to get students ready for general chem, in "preparation for gen chem" courses, substantial time may need to be devoted to overlearning computation.
This is an instructional sequence that cognitive studies recommend for a new topic in science.
Mix in-class at home, in-class, at home, in-class.
Free Resources

   • 50 pages of homework assignment options;
   • FREE for you and students
   • Week1-2 options for all first-year levels
   • Lecture notes with clicker questions
   • Worked-out practice, how to learn

When you have a minute, take a look at this free packet.
Get one of these free books with homework assignment ideas that promote overlearning.
3. More on how the brain works, free, at

4. $22 →

The citations for my slides, plus lots more on cognitive science, are on the web at Point 3 above -- and in a new post at  http://arxiv.org/abs/1608.05006

And finally, you will find Make It Stick very helpful on ways to teach students to learn. We have recently learned much, and are learning more, about what works in learning.
To Learn:
First memorize, then reason.

• Done!
• What’s the ONE thing to remember?
• Sceptical Questions?
• Opposing viewpoints?

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