To the Instructor – (Version 4, 4/14/21)

Preparation for Electrochemistry – A Suggestion for Homework

This packet contains a homework assignment of a type cognitive scientists suggest will help students learn electrochemistry more quickly -- and better retain their learning.

The Importance of Memorized Fundamentals

Cognitive scientists have found that when learning a new topic, student learning is accelerated if at the *start*, instructors

- Define (or refresh memory of) the topic's vocabulary and fundamental relationships,
- Encourage students (with a brief quiz) to make those fundamentals *quickly recallable* from long-term *memory* (LTM),
- *then* ask students to begin to solve most problems.

In the homework assignment below, the initial vocabulary of electrochemistry is reviewed for terms students may have previously studied, and taught for new terms introduced in electrochemistry. Brief quizzes are included to encourage homework completion.

Cognitive science predicts mastering new vocabulary at the start of a topic speeds learning. This assignment in this packet is an experiment to test this prediction in real classes.

The Impact of Working Memory Limits

Why memorize vocabulary first? Why memorize at all when on a cell phone, you can look up needed information?

Scientists who study the brain tell us: Space in *working memory* (where the brain solves problems) is essentially unlimited for information "recallable with *automaticity*" (quickly and accurately) from LTM, but is exceptionally limited for other information.

During problem solving, working memory must hold problem data for processing. If a definition of vocabulary in a problem cannot be quickly recalled, its "looked up" meaning must also be held in the part of working memory that is limited. This additional required storage tends to bump the problem data out of working memory, and confusion tends to result.

Limitations in working memory impact learning as well as problem solving, because learning (storing information in LTM) is a result of processing. If fundamental vocabulary is "recallable with *automaticity*," working memory has more room to hold the concepts, connections, and context in a problem. As a result, those elements are more likely to be stored in LTM as an outcome of processing, which expands conceptual frameworks. If learning vocabulary is delayed, moving concepts, contexts, and connections into LTM is delayed and diminished.

University of Virginia cognitive scientist Daniel Willingham suggests that instructors:

> "[E]xplain to students that automaticity in facts is important because it frees their minds to think about concepts." [1]

(For more on the science of learning, see **Memorizing Fundamentals First: What Science Says**, at the end of this packet.)

The Experiment

The assignment below asks students to learn vocabulary definitions during study time. Topic Day One can then be spent on electrochemistry demonstrations or other forms of active learning. A quiz on the content (supplied below) is recommended on Topic Day 2.

To examine the content, scroll down two pages to the Electrochem Fundamentals page, review the handout and quiz that follows, then return **here**.

Security

This experiment requires a way to give a secure 10 minute quiz. If you are "all remote," the assignment will help some students this year, but more next year.

Suggested Assignment

The handout below is also online as a stand-alone PDF. A suggested assignment format would be to (A) make copies of the handout for students for whom computer access at home may be an issue, but for others to (B) post the following:

> **Homework Assignment – Preparation for Electrochemistry:**
>
> Download the five pages at www.ChemReview.Net/ElectroPrep.PDF
>
> Follow the directions. Be ready for a "no-calculator" quiz on the content on [date].

A Word Doc of the PDF you are reading is posted at https://www.ChemReview.Net/ElectroPrepToInstructors.docx . Feel free to use the docx file to edit the handout or the quizzes.

Sequence

Suggested timing would be:

- Assign the handout as homework, and announce the date the homework quiz will be given (in 2-4 calendar days).
- On class Day One, after assigning the homework, consider demonstrations or a minilab.
- On class Day 2, administer the 10 minute quiz.

How Much to Assign?

How many pages to assign at once, and how much time to allow, will depend on your teaching situation.

The handout assumes that earlier in the course, students studied redox basics. If so, page 1 content will be re-learned quickly. New topics will take more time and effort. If basic redox definitions have *not* yet been studied, you may want to split the packet into two assignments.

If this is your students' first experience with "preparation, flashcards, and quiz" (and if it has been an exhausting Covid year), you might assign the first 2 of 3 content pages this year, and experiment with assigning all pages next year.

The flashcards and quiz are in an order that should ease dividing the assignment into parts.

Day One

The handout enables using Day One for demonstrations. These might include reacting metal strips with solutions of their ions (and discussing coinage metals), the electrolysis of water (and discussing hydrogen as a fuel), or constructing a battery (discussing factors in battery life, *emf*, and recharging).

Flashcards

Scientists who study how the brain learns emphasize the need for *spaced overlearning*: practice at retrieving fundamentals from memory over several days, repeated on occasion thereafter.

Cognitive scientists say that if new vocabulary is overlearned, students will learn to solve problems with more success, in less time, and will better retain content for the final exam -- and (more important) when needed in future courses, and careers. That's the goal.

Evaluation

If the results of this experiment show promise, it will work better, after adjustments, in additional experiments with other topics.

Updates

Please check back on occasion for updated (and sometimes corrected…) versions of this document by clicking on https://www.ChemReview.Net/ElectroPrepToInstructors.PDF .

Additional homework assignments for first-year chemistry are posted at www.ChemReview.Net/blog .

Feedback and suggestions on this packet are appreciated: ToTheAuthors(at)ChemReview.Net .

Hope this helps! -- Eric Nelson

Content shaded or boxed below must be memorized.

Electrochemistry Fundamentals

A **redox reaction** is a transfer of one or more *electrons* (**e**⁻) from one particle to another.

Redox reactions can store and release *energy*. For example, in a battery, a redox reaction causes electrons to flow through wires. That movement of electrons can be harnessed to do useful *work* in powering electronic devices, including cars and cell-phones. Redox reactions also store and supply energy in biological systems.

Redox Terminology

Redox is a term made from the words *reduction* and *oxidation*. **Oxidation** is the loss of electrons. **Reduction** is the gain of electrons. In redox reactions, particles that are:

- **Reducing agents** *lose their electrons* by giving electrons to other particles.
- **Oxidizing agents** *gain* electrons by removing electrons from other particles.

In redox *reactions*, a reducing agent is oxidized and an oxidizing agent is reduced.

For example, the reaction of copper metal with a solution of silver ions can be written as

$$Cu + 2\ Ag^{+} \rightarrow 2\ Ag + Cu^{2+}$$

RA **OA**

The copper metal atoms lose 2 electrons. They are *oxidized*. By donating their electrons to the silver ion, they serve as the *reducing agent* (**RA**) for the Ag^{+}.

Each silver ion gains an electron to become silver metal. The silver ions are therefore *reduced*. By accepting electrons from copper metal, the Ag^{+} acts as an *oxidizing agent* (**OA**): the particle that, by taking an electron, enables the copper metal to be oxidized.

In a redox reaction, one reactant is an RA and the other is an OA.

Half-Reactions

A redox reaction can be separated into two half-reactions. One half-reaction shows the gain of electrons for the reactant that is an oxidizing agent, the other shows the loss of electrons for the reactant that is a reducing agent.

Half-reactions include the symbol $\mathbf{e^-}$ showing the number of electrons gained or lost.

For example, the reaction above can be separated into two half reactions.

$$Cu + 2\ Ag^{+} \rightarrow 2\ Ag + Cu^{2+}$$

- -

$Cu \rightarrow Cu^{2+} + \mathbf{2e^-}$ (the copper metal is oxidized, losing 2 electrons)

$\mathbf{2e^-} + 2\ Ag^{+} \rightarrow 2Ag$ (for each Cu oxidized, 2 silver ions are reduced)

Half-reactions must balance for atoms and charge. To balance half reactions, *first* balance atoms, *then* add $\mathbf{e^-}$ to balance charge.

* * * * *

Practice: Check your answers at the end after each problem.

1. Add electrons to one side to balance these half-reactions.

   a. $Mg \rightarrow Mg^{2+}$ b. $S \rightarrow S^{2-}$

2. Balance these half-reactions.

   a. $H_2 \rightarrow H^+$ b. $Pb^{4+} \rightarrow Pb^{2+}$

3. Write the formulas for any *reactants* in the 4 cases above that are oxidizing agents.

* * * * *

Measuring Charge:

Electrical charge is a fundamental quantity, like distance, mass, or time. The smallest charge encountered in chemistry is the charge on one electron. That negative charge is equal to, but opposite, the positive charge on a proton.

Charge on one electron (e^-) = 1 *fundamental* or *elemental* charge

In the SI system, the unit measuring charge is the **coulomb** (symbol **C**). A precise definition is "one mole of fundamental charges = 96,485.3415 coulombs," but for most calculations three significant figures will suffice.

In a problem, when you see *coulombs* and *electrons*, before starting steps to solve, write:

96,500 coulombs = 1 *mole* of electrons

(This conversion will likely be needed.)

An *amount* of charge that moves can be measured by counting either the *electrons* that move or the *charges* in coulombs that move.

Work, Volts, and EMF

In measuring the work that can be done by moving charges, two factors are important: the number of moving charges *and* the force behind them.

Electromotive force (*emf*, symbol $\mathcal{E}$) can be defined as the work that moving charges can do per unit of charge. The SI unit that measures *emf* is the **volt**.

$$\text{EMF in volts (V)} \equiv \frac{\text{Electrical work in joules (J)}}{\text{Charge in coulombs (C)}}$$

If a problem mentions volts, joules, and coulombs (or any 2), on your paper, write the formula in the box above from memory.

This definition means: **1 volt ≡ 1 joule/coulomb** In calculations involving volts, joules and coulombs, to solve for volts, joules/coulomb must often be solved first.

Redox Tendencies

Each redox half-reaction has a measurable tendency to occur.

For example, molecules of elemental fluorine (F_2) are strong *oxidizing* agents: they have a strong tendency to take electrons away from other substances.

Lithium metal is a strong *reducing* agent. It has a strong tendency to give away one electron. The *half*-reaction for lithium oxidation can be represented as

$$Li \rightarrow Li^{+} + e^{-} \quad \text{(strong tendency to go to the right)}$$

Standard Reduction Potentials

The tendency of particle to donate or attract electrons creates an electromotive force (*emf*, symbol $\mathcal{E}$). Every half-reaction can be assigned a **reduction potential**, an *emf* in *volts* measuring the characteristic tendency of an OA to acquire electrons and be reduced.

There is no logical zero (lowest possible value) for reduction potentials. Instead, we *define* the reduction potential for the *hydrogen electrode* reaction as *zero* volts, and measure reduction potentials in volts relative to that zero value.

At standard conditions (1 atm gas pressure, 1 M ions, and 25ºC), for the reaction

$$2\,H^{+} + 2\,e^{-} \rightarrow H_2 \qquad \mathcal{E} \equiv \mathcal{E}^{o} \equiv \mathbf{0\ volts} \quad \text{(an exact definition)}$$

At the right is a table of selected half reactions. Note the highest and lowest half-reactions.

Standard Reduction Potentials	$\mathcal{E}^{o}$ in volts at 25ºC
$F_2 + 2\,e^{-} \rightarrow 2\,F^{-}$	**+ 2.87**
$Cl_2 + 2\,e^{-} \rightarrow 2\,Cl^{-}$	1.36
$Cu^{2+} + 2e^{-} \rightarrow Cu$	0.34
$2\,H^{+} + 2\,e^{-} \rightarrow H_2$	**0.0**
$Pb^{+2} + 2e^{-} \rightarrow Pb$	− 0.13
$Na^{+} + e^{-} \rightarrow Na$	− 2.71
$Li^{+} + e^{-} \rightarrow Li$	**− 3.04**

In standard reduction potential (SRP) tables:

- S*tandard* means that all solution concentrations are 1 M, all gas pressures are 1 atm, and the temperature is 25ºC.
- When all half-reaction components are at standard conditions, the $\mathcal{E}$ is termed $\mathcal{E}^{\mathbf{o}}$.
- EMF values may be positive or negative.
- The half-reactions have electrons on the left, *reducing* the left-side particle. The form is:

  OA + electrons → RA

- The strongest *oxidizing agent* (the particle with the highest tendency to be reduced) has the highest reduction potential (the highest positive value).
- If a particle is a *strong* RA or OA on one side of →, the particle on the other side is *weak*.
- When the $\mathcal{E}^{o}$ values are listed highest to lowest, the *strongest reducing agents* (RA) are at the *bottom right* of the table. Why? The weakest oxidizing agents are at the bottom *left*. When they gain the electrons, they becomes strong reducing agents.

* * * * *

Answers to **Problems** above:

1a. . Mg → Mg^{2+} + **2 e^-** 1b. S + **2 e^-** → S^{2-} 2a. H_2 → **2** H^+ + **2e^-**

2b. **2 e^-** + Pb^{4+} → Pb^{2+} 3. S , . Pb^{4+} (oxidizing agents gain electrons when they react)

* * * * *

Suggested Flashcards

Cognitive science tells us the fastest way to learn new vocabulary in a foreign language (including chemistry) is *retrieval practice* using flashcards. To remember meanings long-term, use *spaced overlearning*: Practice the cards to perfection 3 days in a row, then about a week later, then about a month later.

Make the following 3 x 5 inch flashcards. If needed, see the detailed instructions at https://www.chemreview.net/FlashCards.pdf

1. For facts that only make sense in one direction, make "one-sided cards." Take a few cards, cut a corner off the top right (\ ), write the question on the front and answer on the back. When you run the deck, keep the notch cut at the top right.

   To see which flashcards you need to make, for the following cards, cover the *right* column, then put a check on the left if you can answer the left column question *quickly* and correctly.

   Which cards you need will depend on your prior knowledge, but when in doubt, make the card. On fundamentals, you need quick, confident, accurate recall—every time.

   When done, if a row does not have a check, write the card.

Front-side of cards (with \ corner cut at top right):	Back Side -- Answers
In redox, one reactant is an ___ and one an ___	one is RA and one is OA
Half reactions include the symbol ___…	**e^-** (electron)
Half reactions must be balanced for ______…	atoms and charge
To balance half reactions, first ____________	first balance atoms, then balance charge w/ **e^-**
EMF is an abbreviation for ___	electromotive force
A reduction potential is measured in what units?	Volts
In an SRP table, SRP stands for	Standard reduction potential
The format for an SRP table is electrons on the __	left of the arrow
The rxn. w/ SRP of 0 V has ____ ions on left	2 H^+
One particle with a high positive $\mathcal{E}^o$ is ____	F_2
One particle with a very negative $\mathcal{E}^o$ value is ___	Li^+

2. For relationships that must be memorized in both directions, make "two-sided cards." by using the cards as they are, with*out* a corner cut, and practice them in both directions.

For these, first cover the *right* column, then put a check on the left if you can answer the left column question *quickly* and correctly. Then cover the *left* column and check the right side if you can answer the right-side *automatically*.

When done, if a row does not have two checks, make the flashcard.

Two-sided cards (with*out* a notch):

A redox reaction is ___	A transfer of electrons between particles is ___
Oxidation is ___	The loss of electrons is ______
Reduction is ______	The gain of electrons is _____
In a reaction, a *reducing* agent becomes ___	The particle *oxidized* is which agent?
In a reaction, an *oxidizing* agent becomes ___	The particle *reduced* is which agent?
The charge on one electron =	1 *fundamental* or *elemental* charge
96,500 coulombs = _________	____ coulombs = charge of 1 mole of $\mathbf{e^-}$
EMF is measured in _______	Volts is a measure of ______
EMF in volts (V) ≡	Work in joules (J) / Charge in coulombs (C) =
1 volt =	1 joule/coulomb =
An example of a strong OA is _____	F_2 is a strong _________
An example of a strong RA is _____	Li is a strong _________

Practice Quiz

Run the flashcards 3 days, then, before the real quiz, complete this practice quiz. Do NOT use a calculator. Do needed math on scratch paper.

1. In reactions, ____________ agents lose elections. ______________ agents are oxidized.
2. Balance these half-reactions.

   a. $I_2 \rightarrow I^-$ b. $Cu^+ \rightarrow Cu^{2+}$
3. Write the formula(s) for any reactants in 2a and 2b that are oxidizing agents.
4. Half a mole of electrons contain how much charge?
5. If 4.0 coulombs of electron charge can do 24.0 Joules of work, what is the *emf* moving the electrons?
6. How much work can be done by half a coulomb of electron charge moving with an *emf* of 5.0 volts?
7. In an SRP table with highest positive values at the top, where is the strongest OA?
8. Write the name and symbol for a very strong reducing agent.

* * * * *

Answers: 1. Reducing, reducing 2. $\mathbf{2\,e^- + I_2 \rightarrow 2\,I^-}$ 2b $Cu^+ \rightarrow Cu^{2+} + \mathbf{e^-}$ 3. I_2

4. 48,300 C 5. 6.0 V 6. 2.5 J 7. Top left 8. Lithium (Li) or sodium (Na)

To Instructors --

10 Minute Quiz on Electrochemistry Fundamentals

Below are short quizzes on the content of the Electrochemistry Fundamentals handout.

The quiz is "no calculator." There is one simple multiplication of a type they need to be able to do to work in the sciences.

It should take 10 minutes. It is designed to be easy if students completed the homework.

There are 3 copies with scrambled questions that may be handed out in an alternating order if security is a concern.

The quiz is intended to be closed notes and given in a class meeting when security can be maintained.

If classes are all online and/or security is not possible, you might simply post one quiz during online class on the day the assignment is due, ask students to work on it, and then go over the answers. It's not ideal but should help those who understand the cognitive benefit of a "self-quiz."

Answer Key

Quiz 1 (4.00 to start Q4)

1. Oxidizing, oxidizing 2a. **2** $Br^{-} \rightarrow Br_2$ + **2 e⁻** 2b Fe^{3+} + **3e⁻** → Fe 3. Br^{-}

4. 386,000 C 5. 16 Joules 6. 3.0 Volts 7. F_2 8. $2\,H^{+} + 2\,e^{-} \rightarrow H_2$ 9. **0** Volts

Quiz 2 (6.00 to start Q6)

1. Oxidizing, reducing 2b **3e⁻** + $Al^{3+} \rightarrow Al$ 2b. **2 e⁻ +** $Cl_2 \rightarrow$ **2** Cl^{-} 3. Cl_2

4. 24 Joules 5. 4.0 Volts 6. 579,000 C 7. $2\,H^{+} + 2\,e^{-} \rightarrow H_2$ 8. **0** Volts 9. F_2

Quiz 3 (8.00 to start Q4)

1. Reducing, reducing 2a. $Au \rightarrow Au^{3+}$ + **3e⁻** 2b. **2** $Br^{-} \rightarrow Br_2$ + **2 e⁻** 3. Au and Br^{-}

4. 772,000 C 5. 2.0 Volts 6. 12 Joules 7. Li or Na 8. $2\,H^{+} + 2\,e^{-} \rightarrow H_2$ 9. **0** Volts

Name: ______________________________ Section __________

Quiz On Electrochem Fundamentals

Do *not* use a calculator. Write answers in or after the questions. Complete needed math at the bottom of this paper, then transfer the answer to after the question.

1. In reactions, ____________ agents gain elections. ___________ agents are reduced.

2. Balance these half-reactions.

   a. $Br^{-} \rightarrow Br_2$ b. $Fe^{3+} \rightarrow Fe$

3. Write the formula(s) for any reactants in 2a and 2b acting as reducing agents.

4. 4.00 moles of electrons contain how much charge?

5. How much work can be done by 8.0 volts moving 2.0 coulombs of electron charge?

6. If 9.0 Joules of work are done by 3.0 coulombs of moving electron charge, what is the *EMF* moving the electrons?

7. Write the symbol for a very strong oxidizing agent.

8. Write the half-reaction for the reduction of protons to hydrogen gas.

9. What is the standard reduction potential for the half-reaction in problem 8?

Name: ____ Section ___________

Quiz On Electrochem Fundamentals

Do *not* use a calculator. Write answers in or after the questions. Complete needed math at the bottom of this paper, then transfer the answer to after the question.

1. In reactions, ______________ agents gain elections. _____________ agents are oxidized.

2. Balance these half-reactions.

   a. $Al^{3+} \rightarrow Al$ b. $Cl_2 \rightarrow Cl^{-}$

3. Write the formula(s) for any reactants in 2a and 2b acting as oxidizing agents.

4. How much work can be done by 12.0 volts moving 2.0 coulombs of electron charge?

5. If 12.0 Joules of work are done by 3.0 coulombs of moving electron charge, what is the *EMF* moving the electrons?

6. 6.00 moles of electrons contain how much charge?

7. Write the half-reaction for the reduction of protons to hydrogen gas.

8. What is the standard reduction potential for the half-reaction in problem 7?

9. Write the symbol for a very strong oxidizing agent.

Name: ____ Section ____________

Quiz On Electrochem Fundamentals

Do *not* use a calculator. Write answers in or after the questions. Complete needed math at the bottom of this paper, then transfer the answer to after the question.

1. In reactions, ______________ agents lose elections. ______________ agents are oxidized.

2. Balance these half-reactions.

   a. $Au \rightarrow Au^{3+}$ b. $Br^{-} \rightarrow Br_2$

3. Write the formula(s) for any reactants in 2a and 2b acting as reducing agents.

4. 8.00 moles of electrons contain how much charge?

5. If 8.0 Joules of work are done by 4.0 coulombs of moving electron charge, what is the *EMF* moving the electrons?

6. How much work can be done by 6.0 volts moving 2.0 coulombs of electron charge?

7. Write the symbol for a very strong reducing agent.

8. Write the half-reaction for the reduction of protons to hydrogen gas.

9. What is the standard reduction potential for the half-reaction in problem 7?

To Instructors --

Memorizing Fundamentals First: What Science Says

Below are FAQs on the science of learning. (You can find citations for this science at https://arxiv.org/abs/2102.00454)

1. **For students, what is the goal of study?**

   Scientists who study how the brain learns tell us that the goal of study, for each new topic, is to wire into the brain's long-term memory (LTM) a conceptual framework (also called a schema) for the topic. A well-organized framework tells us automatically, when given a problem, what facts and procedures to recall and apply to the problem's data to reach the problem goal.

   Experts in a field have a vast conceptual framework in LTM for their field of expertise.

   For students seeking a career in a scientific field, the initial goal is to construct a basic framework, from fundamentals, for each topic necessary for work in the field. Once an initial framework is constructed, the brain stores additional new knowledge for the topic more easily.

2. **How does the brain construct a conceptual framework for fields with well-structured knowledge, such as math, physical sciences, and engineering?**

   Building a framework is done in two steps. First, new knowledge must be stored in the *neurons* of the brain's LTM: specialized cells that can store knowledge. Each neuron can grow hundreds of wires connecting to other neurons.

   When a new technical term and its precise definition are learned, what is stored must have two parts: The new image or sound or other sensation being learned, plus the already-known elements of knowledge used to define the new knowledge.

   The letters of its written word, how it is pronounced, and the words of its definition are all stored in separate "memory traces" in neurons. The new word and its definition are connected by wiring among the neurons that store each of them.

   Viewing or *hearing* or *saying* a definition causes neurons storing the words involved to *fire*, which means to send out an electrical impulse to the neurons to which they are connected by wiring. When a neuron fires, it *activates* so that the information it stores can be recalled into working memory to solve a problem.

   In addition, when a neuron fires, it to tend to grow wiring that connects it to other neurons that fire at the same time when solving a problem. In neuroscience, a fundamental (simplified) rule is: "Neurons that fire together, wire together."

   After neurons holding the word and its definition are connected, encountering *either* the word *or* its definition causes the other part to fire, activate, and become recallable into LTM for use in solving a problem.

Repeated practice at recall is required to move new elements of knowledge into neurons and then grow physiological wiring between the neurons storing related elements.

3. **What's step 2?**

   Once a fundamental definition, fact, relationship or procedure is quickly recallable, when it is recalled to solve a problem, the act of recall tends to promote wiring to the other elements being processed to solve the problem. Steps of problem solving perceived as successful by the brain tend to cause additional wiring to grow or strengthen within the conceptual framework.

   To *learn* is to add small elements of new knowledge to neurons and then, by solving problems, to wire them to related elements.

4. **Why not just learn meanings gradually, in the context of solving problems?**

   If a student starts to solve problems before fundamentals are recallable, the focus in a problem tends to be "what do the words mean" rather than "what are the relationships among them." This slows and diminishes the ability of the problem solving to wire the relationships among the concepts, connections, and context.

5. **Why prepare a handout? Why not assign learning the vocabulary by reading the General Chemistry text?**

   General Chemistry textbooks are filled with great diagrams, worked examples, and problems. They cover each topic in rich detail. But at the start of a topic, a student needs to begin construction of a *minimum essential framework* in their LTM. After that basic schema is constructed, the brain has less difficulty storing additional new information, in part because of understanding where the information *fits* in the framework.

   In a detailed reference text, students may have difficulty identifying what vocabulary and other elements of knowledge are the most important to make initially recallable. But once those fundamentals identified by the instructor are recallable, students can read a reference text with improved comprehension and add information from their reading to their topic framework.

6. **Why is learning science difficult?**

   Major bottlenecks include

   A. The initial storage of a technical term and its precise definition requires repeated mental effort. Without effort and repetition, storage in LTM tends to be temporary. The goal of study is *long*-term information storage.

   B. If a fact or definition is not *quickly* recallable, it tends to clog working memory during problem solving. This means, to work around working memory limits, facts and term definitions and procedures encountered frequently must be *very* well memorized.

Cognitive experts David Geary, Daniel Berch, Wade Boykin, Susan Embretson, Valerie Reyna, and Robert Siegler) write:

> "[F]acts and fundamental algorithms should be thoroughly mastered, and indeed, over-learned, rather than merely learned to a moderate degree of proficiency."[2]

C. To build a framework for a topic, procedures and concepts must be moved into LTM during problem solving. Because of working memory limits, that process is slow until vocabulary and fundamental relationships are recallable with automaticity.

D. To retain recall of fundamentals requires *spaced overlearning*: repeated practice at recall over multiple days, and occasionally thereafter.

E. To wire the brain requires focused *attention* on the problem. During learning, if the student is distracted (such as by cell-phone buzz), attention tends to be lost.

7. What makes learning easier (relatively)?

Willingham writes:

> "Knowledge is not only cumulative, it grows exponentially. Those with a rich base of factual knowledge find it easier to learn more—the rich get richer."[3]

Initial learning in a topic is difficult, but as a framework gradually gains shape, additional knowledge fits into it more easily.

8. In General Chemistry, what's the role of the instructor?

Cognitive experts say: Because there are physiological limits on how much new knowledge the brain can wire into memory each day, the fundamentals we ask students to make quickly recallable must be those that are most important. This suggests our role, for each new topic, is

- Identify what elements of knowledge are most essential in constructing an initial schema for a topic.
- Supply the knowledge gradually and in a logical order.
- Provide frequent incentives for students to make essential fundamentals quickly recallable from memory.
- After initial recall is achieved, supply simple problems to learn concepts.
- Because of working memory limits, to solve more complex "end-of-chapter" problems, students must be taught and must practice recalling and applying efficient, effective algorithms.
- Conduct demonstrations that pose problems. Live, visual chemistry adds rich contextual elements to frameworks.

9. In General Chemistry, what's the goal for students?

The brain solves problems using relationships it can quickly recall from memory. For each new topic, the student must

- Work to move into memory definitions and relationships identified by the instructor as fundamentals,
- Apply those relationships to solve problems that construct an initial conceptual framework for the topic.
- Use flashcards and recall during problems to gradually *overlearn* fundamentals so they will remain recallable long-term.

Instructors must supply key knowledge. Students must store the knowledge and by problem solving, wire understanding.

10. How do we know this is what *science* says?

Quotes and citations from scientists who study the brain are at https://arxiv.org/abs/2102.00454 . You are encouraged to reach your own understanding of what scientists cited in the article are saying.

11. Additional Resources

For classes at any level of general chemistry or preparation for general chemistry, a homework assignment similar to the above -- on definitions for prefixes and fundamentals of the *metric system* -- is available at www.ChemReview.Net/ExpoMetric.PDF

Bottom Line?

Chemistry is about molecules and math.

Chemistry *instruction* is about molecules, math, and memory.

By learning how science says the brain adds to memory and applies memory to solve problems, we can design more effective instruction.

-- Eric (rick) Nelson

References

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