Teaching students how we think, not what we know
A curricular transformation story

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“Let’s teach how we think instead of what we know”
Vicente Talanquer and John Pollard
Components Needed for Curricular Transformation

From our experiences, curricular transformation is multi-faceted

- Motivation
- Time
- Institutional Support
- Content Rethinking
- Instructional Redesign
The Motivation

Teaching and Learning General Chemistry
Our View

The current General Chemistry Curriculum is too monolithic and has serious limitations:

Breadth vs. Depth
Segmentation vs. Integration
Knowledge vs. Reasoning
Algorithmic vs. Conceptual
Tradition vs. Relevance

Impact on student learning and motivation
The Challenge

How to “reconceptualize” the curriculum to:

- Make it more intellectually stimulating;
- Present a more coherent view of chemistry;
- Better reflect the nature and power of “chemical thinking.”
The Guiding Question

How to develop an alternative curriculum focused on analyzing the power of “chemical thinking” vs. “chemical knowledge”?

Main Focus Shifts

From topics → To questions
From academic → To contextual
From what we know → To how we think
What fundamental questions does “chemical thinking” allow us to answer?

- Analysis
  - What is this?

- Transformation
  - How do I change it?

- Synthesis
  - How do I make it?

- Modeling
  - How do I explain it?

*NRC. Beyond the Molecular Frontier, 2001.
In which areas is “chemical thinking” likely to be most relevant in the XXI\textsuperscript{st} century?

- Environmental Issues
- Material’s Design
- Life and Medicine
- Energy Sources
Knowing → Thinking

What “enduring ways of thinking” do we want students to develop?

EXAMPLE:

Analysis
What is this?

Assumptions?
Existence of a Differentiating Characteristic

Intellectual Tools?
Structure → Properties Relationships

Experimental Tools?
Spectroscopic Techniques
Making it Happen

Curriculum Design

Core Elements

- Essential Questions
- Enduring Understanding
- Core Concepts

Learning Experiences

Evidence of Understanding (Assessments)
Essential Questions

<table>
<thead>
<tr>
<th>Units</th>
<th>Modules</th>
</tr>
</thead>
</table>
| 1                   | M1. Searching for differences  
                      | M2. Modeling matter  
                      | M3. Comparing masses  
                      | M4. Determining composition |
| 2                   | M1. Analyzing light-matter interactions  
                      | M2. Looking for patterns  
                      | M3. Predicting geometry  
                      | M4. Inferring charge distribution |

1. How do we distinguish substances?

2. How do we determine structure?

CONTEXTS:

What is in our air?

What is in a star?
## Core Concepts

What do we need to know to answer the question?

<table>
<thead>
<tr>
<th>Units</th>
<th>Core Chemistry Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>How do we distinguish substances?</strong></td>
</tr>
<tr>
<td></td>
<td>Phase Properties and Transitions</td>
</tr>
<tr>
<td></td>
<td>Particulate Model of Matter</td>
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<tr>
<td></td>
<td>Energetics and Entropy</td>
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<tr>
<td></td>
<td>Element/Compound; Atom/Molecule</td>
</tr>
<tr>
<td></td>
<td>Mole/Molar Mass; Elemental Composition</td>
</tr>
<tr>
<td>2</td>
<td><strong>How do we determine structure?</strong></td>
</tr>
<tr>
<td></td>
<td>Light-Matter Interactions</td>
</tr>
<tr>
<td></td>
<td>Atomic Structure</td>
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<tr>
<td></td>
<td>Covalent Bonding</td>
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<tr>
<td></td>
<td>Molecular Geometry and Polarity</td>
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<tr>
<td>3</td>
<td><strong>How do we predict properties?</strong></td>
</tr>
<tr>
<td></td>
<td>Intermolecular Forces</td>
</tr>
<tr>
<td></td>
<td>Molecular and Macromolecular Compounds</td>
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<tr>
<td></td>
<td>Ionic Compounds</td>
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<tr>
<td></td>
<td>Metallic Systems</td>
</tr>
</tbody>
</table>
An Example: Unit 1

UNIT 1

How do we distinguish substances?

Our world is characterized by its diversity at all levels, from the wide variety of living organisms to the multitude of materials that make everything that surrounds us. Understanding the diversity of the material world has been particularly important for our survival on the planet. The ability to detect, identify, separate, and quantify different types of substances has allowed humans to take advantage of the many natural resources that Earth has to offer. These same abilities are also likely to help us save the planet from the environmental consequences of our decisions and actions.

The central goal of this Unit is to help you understand and apply basic ideas and ways of thinking that can be used to distinguish the different substances present in a variety of systems of interest. Although the ideas and models that we will discuss are useful in many relevant contexts, it is important that we will analyze many examples related to our own planet’s atmosphere, trying to answer questions such as:

What is it made of?
How do we separate its components?
How do we identify them?
How do we explain their properties?
How do we model their behavior?

UNIT 1 MODULES

M1. Searching for Differences
Identifying differences that allow us to separate components.

M2. Modeling Matter
Using the particulate model of matter to explain differences.

M3. Comparing Masses
Characterizing differences in particle mass and number.

M4. Determining Composition
Characterizing differences in particle composition.
Module 1

Search for differentiating characteristics:

- Intensive Properties
- Phase Change Behavior (LECTURE)
- Density (LAB)
- Separation Identification

Earth’s Atmosphere as Case Study

Chemical Thinking

Module 1

Searching for Differences

Most things in our surroundings are, from the chemical point of view, complex systems composed of many substances in different states of matter. Take, for example, something as common as the air we breathe. It consists at least of three different substances, from oxygen gas to temporary water droplets to solid as dust particles. This chemical complexity can be seen as a blessing and a curse. On the one hand, the diversity of substances and phases in our world has allowed the emergence of life on our planet and the development of the rich natural resources that sustain it. On the other hand, the large number of substances that can be found in a single breath makes it difficult the detection, identification, and isolation of the things that can threaten our life.

The initial source of all our bodies and most of the materials with which we interact on a daily basis pose a significant challenge to many professionals. How do we detect the presence of chemicals in a complex mixture such as our blood? How do we identify the pollutants that may be present in our drinking water? How do we know what substances can be found in the soil and rocks or to the chemicals that we extract from the ground? The answers to these questions require some chemical thinking. For example, consider this challenge:

**THE CHALLENGE**

Extracting Oxygen

Imagine that you were involved in extracting pure oxygen from the atmosphere for commercial purposes. You would also be involved in the treatment of patients with thoracic disease, and other respiratory ailments.

- How would you extract oxygen from air?
- What properties of this substance would help you separate it from other air components?

Make a list of potential strategies that you would follow to solve this problem. Then, share and discuss your ideas with one of your classmates.

This module will help you develop the type of chemical reasoning that is used to answer questions similar to those posed in the challenge. In particular, the central goal of the module is to help you recognize distinctive properties of chemical substances that can be used to identify and separate them.
Module 2

Explaining Differences:

- KMT
- IMFs
- TLC (LAB)

Particle Composition/Structure

Types of Substances
Module 3

Differentiating Particles:

- Relative Mass
- Molar Mass
- Amount of Substance
- TLC-AS (LAB)

Quantification
Module 4

Differentiating Particles:

Determining Composition

Measuring Relative Mass (MS)

Determining Elemental Composition

Empirical and Molecular Formulas
1. How do we distinguish substances?
2. How do we determine structure?
3. How do we predict properties?
Unit Learning Objective

By the end of this UNIT students should be able to:

Given information about the phase behavior, the mass spectrometry, and the elemental analysis of the chemical components of a relevant system:

Design/Implement strategies to:

Identify, Separate, Characterize, Quantify, Explain the Behavior of main components
Chemical Thinking

Contexts of Application

Exploring Titan

Chemistry 231

Let’s Apply

VOCs in Water

Refrigerants

Oil Spill

Refining Petroleum

Let’s Apply

Chemical Thinking
Course Sequence

Substances

1. How do we distinguish substances?

4. How do we model chemical change?

7. How do we make new substances?

Processes

2. How do we determine structure?

5. How do we predict chemical change?

8. How do we harness chemical energy?

3. How do we predict properties?

6. How do we control chemical change?

7. How do we make new substances?
Modeling Matter

The assumption that every single substance in our surroundings has at least one differentiating characteristic that makes it unique is at the base of all of the chemical techniques used to analyze our world. What causes these differences? Why is it that a substance like water boils at 100 °C while oxygen boils at -183 °C? Why is carbon dioxide a gas at room temperature while pure carbon is a solid under the same conditions? To try to explain these differences, humans through history have developed “models” of matter. Models are simplified representations of objects or processes built to better describe, explain, predict, and even control their properties and behavior. Some of these models may be concrete, as the model of a bridge used by an engineer to understand how the system will respond to stress. Some models are abstract, composed of entities that may be treated as tangible objects (e.g., force, energy) but actually represent concepts or ideas that help us make sense of properties and events.

Modeling substances and processes is at the core of chemical thinking. It is through modeling that chemists have been able not only to analyze and explain the diversity of the material world, but to design strategies to create new materials. Many of the models used in chemistry are abstract and refer to entities that cannot be seen by the naked eye. That sometimes makes chemical thinking challenging.
Resources
Chemical Thinking YouTube Channel
<table>
<thead>
<tr>
<th>Regular General Chemistry Units</th>
<th>“Chemical Thinking” Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Atoms and Elements</td>
<td>I. How do we distinguish substances? (4,10,1,2)</td>
</tr>
<tr>
<td>2. Molecules, Compounds, and Chemical Equations</td>
<td>II. How do we determine structure? (6,7,8,9)</td>
</tr>
<tr>
<td>3. Chemical Quantities and Reactions</td>
<td>III. How do we predict properties? (8,9,10,11)</td>
</tr>
<tr>
<td>4. Gases</td>
<td>IV. How do we characterize chemical change? (2,3,5,13)</td>
</tr>
<tr>
<td>5. Thermochemistry</td>
<td>I. How do we predict chemical change? (5,16,14,12)</td>
</tr>
<tr>
<td>6. The Quantum Model of the Atom</td>
<td>II. How do we control chemical change? (3,13,11,14,15)</td>
</tr>
<tr>
<td>7. Periodic Properties of Elements</td>
<td>III. How do we synthesize chemical substances? (12,14,16)</td>
</tr>
<tr>
<td>8. Chemical Bonding</td>
<td>IV. How do we harness chemical energy? (6,7,8,17)</td>
</tr>
<tr>
<td>9. Molecular Structure</td>
<td></td>
</tr>
<tr>
<td>10. Liquids, Solids, and Intermolecular Forces</td>
<td></td>
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<tr>
<td>11. Solutions</td>
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<tr>
<td>12. Chemical Kinetics</td>
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<tr>
<td>13. Chemical Equilibrium</td>
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<tr>
<td>14. Acids and Bases</td>
<td></td>
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<tr>
<td>15. Aqueous Ionic Equilibrium</td>
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<tr>
<td>16. Free Energy and Thermodynamics</td>
<td></td>
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<tr>
<td>17. Electrochemistry</td>
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</tbody>
</table>
Content Focus Decisions

In this process we both eliminated and added (or rebalanced) content within the course.

- Irrelevant to our population
- Unimportant or exotic to the core thinking in our field
- Injected ideas that are relevant to the modern core thinking of our field
- Shifted and rebalanced important core concepts
Making it Happen

Curriculum Design

Essential Questions
Enduring Understandings
Core Concepts

Learning Experiences

Evidence of Understanding
(Assessments)

Core Elements
Let’s Think and Predict

Consider the following teaching study: 3 different groups of college students received different kinds of instruction about schema theory and memory and then completed a transfer task where they asked to make detailed predictions about the results of a new memory study.

Group 1: Read and summarized a text on the topic of schema theory and then listened to a lecture to help them organize their knowledge and learn with understanding.

Group 2: No text reading. In class actively compared simplified data sets from schema experiments on memory then heard the same lecture as group 1.

Group 3: Spend twice the time with data sets activity in class but had no lecture.

Which group would you predict did best on the transfer task?
A Commonly Held Inaccurate Model of Teaching and Learning

Bill Watterson,
*Calvin and Hobbs*

Eventually, Billy came to dread his father's lectures over all other forms of punishment.
Does your class intellectually engage your students and deepen their conceptual understanding and critical thinking ability or does it reinforce the memorization of facts and declarative knowledge?

Bloom’s Taxonomy of Educational Objectives

declarative knowledge
comprehension
application
analysis
synthesis
evaluation
Key results from research into cognition and instruction

- Learning is productive / constructive - learning requires mental effort.
- Knowledge is associative / linked to prior mental models and cognitive structures.
- The cognitive response is context dependent – what and how you learn depends on the educational setting.
- Most people require some social interactions in order to learn deeply and effectively.
- A “metacognitive” approach to instruction can help students learn to take control of their own learning and monitor progress.


Joe Reddish, 2001. AAPT, San Diego
Learning Experiences

How do we develop “student understanding”?

Learning Cycle

- Lecture/Discussion
  - ~300 students

Small Group Activities

Exploration → Concept Development → Concept Application → Exploration
Learning Experiences

Group Activities: Through the Modules

Let’s Think

Use the simulation to test your predictions

Available at: http://www.chem.arizona.edu/chemt/C21/sim

Exploration or Application
Learning Experiences

Group Activities: Through the Modules

MoLE
Molecular Bench

Exploration or Application
Learning Experiences
Learning Experiences
Learning Experiences

Group Activities: Laboratory

Activities require students to:

- Develop their own plans;
- Collect and analyze relevant data;
- Relate claims to evidence;
- Exchange and communicate ideas.

Your Challenge

Imagine that you work for a company that is interested in using superabsorbent polymers, in particular sodium polyacrylate, as ion and molecule “scavengers” for removal of toxic substances dissolved in water.

Your task is to design a set of experimental procedures to characterize the capacity of the polymer to absorb a variety of dissolved substances.

SWH approach
Making it Happen

Curriculum Design

Core Elements

Essential Questions
Enduring Understandings
Core Concepts

Learning Experiences

Evidence of Understanding (Assessments)
How do we assess “student understanding”? 

UNIT 

M1 M2 M3 M4 

Overarching Learning Goals 

Specific: 

Understanding Goals 
Central Ideas 
Performance Outcomes 

FORMATIVE and SUMMATIVE assessments
U2. How do we determine structure?

M1. Analyzing light-matter interactions
Formative Assessment

END OF UNIT

Are You Ready?

The Challenge
The determination of a substance’s identity based on the analysis of its molecular structure is a fundamental analytical tool in forensic science.

Consider this case described in the SFC in May 13, 2001:
In the thick of evening traffic earlier this year, a minivan broke from the grindlock on interstate 580, leveled a call box and continued out of control onto the streets of Livermore. The van struck several parked cars and pedestrians scattered as it shot through a shopping plaza and lurched onto a concrete island. Police found the 30-year-old driver drooling on himself, his hands clenched to the steering wheel. They assumed he was drunk, but the "beverage" police found in the van wasn’t alcohol.

Let’s think!
The analysis of the “beverage” revealed the presence of a liquid substance with the following elemental composition and mass spectrum:

- 53.31% C
- 11.19% H
- 35.51% O

Determine the empirical and molecular formulas of this compound.

Let’s think!
The IR spectrum of the compound is shown below.

Draw the Lewis structures of at least 3 possible compounds given the information that you have.

Let’s think!
These are some of the possible structures:

What physical properties could we use as differentiating characteristic?

Let’s think!
The illegal drug is identified as 1,4-butanediol or BD. It is also known as “One Comma Four” or “One Four Bee” by its users.

Draw a 3D structure of the compound using wedges and dashed lines. Provide the electron pair and molecular geometry around each C and O atom.

Integration

U2. How do we determine structure?
Summative Assessment

Thematic Exams

Titan or Saturn VI is the largest moon of Saturn, the only moon known to have a dense atmosphere, and the only object other than Earth for which clear evidence of stable bodies of surface liquid has been found. The Cassini-Huygens robotic spacecraft mission arrived in Saturn in 2004 and is currently studying the chemical composition of this planet and its moons, including Titan. The following table and graphs summarize important information about this moon.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average surface temperature</td>
<td>93.7 K</td>
<td>This temperature does not vary much during the day or the seasons (min ~90 K; max 94 K)</td>
</tr>
<tr>
<td>Average surface pressure</td>
<td>1.47 bars</td>
<td>The atmospheric pressure on Earth is close to 1 bar.</td>
</tr>
<tr>
<td>Air density at ground level</td>
<td>5 kg/m³</td>
<td>The air density on Earth is 1.2 kg/m³</td>
</tr>
<tr>
<td>Atmosphere composition (% in Volume)</td>
<td>95 % N₂, 5% CH₄</td>
<td>Compared to ~98% N₂; 21% O₂ in our planet</td>
</tr>
<tr>
<td>Hydrosphere composition (% in Mass)</td>
<td>72% C₂H₆, 22.4% CH₄; 5.6% N₂</td>
<td>Compared to ~100% H₂O in our planet</td>
</tr>
</tbody>
</table>

**Temperature in Titan**

**Atmospheric Pressure in Titan**

U1. How do we distinguish substances?
Examinations

I. No significant difference ACS exam:

60.8% (REG) vs. 60.6% (CT)

This is a positive outcome given that the ACS exam has a heavy component of algorithmic problem solving not directly addressed in the new course.

II. Significant difference (t-test; p<0.01) in a conceptual chemistry questionnaire:

44.3% (REG) vs. 55.3% (CT)
## Attitudes

<table>
<thead>
<tr>
<th>Agree? Strongly Agree?</th>
<th>CT %</th>
<th>REG %</th>
</tr>
</thead>
<tbody>
<tr>
<td>The material in this course was something I was interested to learn about</td>
<td>80.2</td>
<td>48.0</td>
</tr>
<tr>
<td>I found the content of this course challenging by rewarding</td>
<td>85.4</td>
<td>57.6</td>
</tr>
<tr>
<td>Chemistry is one of my favorite subjects</td>
<td>50.7</td>
<td>35.8</td>
</tr>
<tr>
<td>The material presented in this class was relevant to me</td>
<td>79.7</td>
<td>37.8</td>
</tr>
<tr>
<td>I am willing to spend some time reading about chemistry topics</td>
<td>54.5</td>
<td>34.3</td>
</tr>
<tr>
<td>If I had a chance, I would like to do a research project in chemistry</td>
<td>46.2</td>
<td>32.5</td>
</tr>
</tbody>
</table>

N = 799

N = 216
Students

Positive student feedback:

“The class is very conceptual and looks very in-depth at everything you learn. The class is very interactive with a lot of in-class activities. You talk a lot about real world applications of chemistry, you have to apply concepts a lot and not just memorize facts and equations.”

“This course taught us how to observe and learn about the world by using chemical thinking. This course was extremely conceptual which is why at times it was difficult.”

There was also student pushback:

Too hard, challenging exams, refuse to participate
Non-Majors OCHEM Grades  F10

Regular (N = 847)

Chemical Thinking (N = 125)
Non-Majors OCHEM Grades  F11

Regular (N = 721)

Chemical Thinking (N = 129)
Departmental Support

Given our experience working with the Chemical Thinking curriculum and our evaluation results we proposed that:

The Chemical Thinking curriculum be implemented for all regular General Chemistry sections starting Fall 2014.

Voted YES with a 5:1 majority
Institutional Support

Awarded to 8 institutions across the country

Our proposal focused on reforms in

Biology
Engineering (computer and chemical)
Physics
Chemistry

Curricular Reform Projects

Faculty Learning Communities

Induce a Cultural Change
What Can I do Besides Lecture to Engage Students in their Learning?

• Ask students questions (not all questions are equal)
• Use interactive videos, demonstrations, animations, and simulations
• In-class writing (with or without discussion)
  – Muddiest Point
  – Summary of Today's Main Points
  – Writing Reflections
• Think-Pair-Share or Peer Instruction
• Small Group Interactions
  – Concept Maps
  – Case Studies
  – Sorting Tasks
  – Ranking Tasks
  – Lecture-Tutorials
• Student Debates (individual/group)
• Whole Class Discussions
More From Educational Research

Engaging students in small group discussions and/or problem solving
Amount of time lecturing less than 60% of total time

List of topic-specific competencies (skills, expertise, …) students should achieve (what students should be able to do)

Students read/view material on upcoming class session and complete assignments or quizzes on it shortly before class or at beginning of class

Problem sets/homework assigned and contributed to course grade at intervals of 2 weeks or less

Encouragement and facilitation for students to work collaboratively on their assignments

Read literature about teaching and learning relevant to this course AND sit in on colleague's class (any class) to get/share ideas for teaching
Final Remarks

The Chemical Thinking curriculum is a rigorous innovative approach to teaching General Chemistry developed based on results of Chemical Education Research:

- Conceptual Understanding
- Chemical Thinking
- Learning Progressions
- Modeling
Transformation in Your Discipline

Conceptual Understanding

Forestry Thinking

Learning Progressions

Modeling
Transformation in Your Discipline

Conceptual Understanding

Sociology Thinking

Learning Progressions

Modeling
Transformation in Your Discipline
Thank You For Your Time

Best of luck for the
Spring 2014 semester
and beyond…