



**Tools and Resources**

***“Feeding the World:
A Story of Guano, War, and Invention”***

October/November 2018

<http://www.acs.org/chemmatters>

**Teacher’s Guide:**



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**Tools and Resources**

***“Feeding the World: A Story of Guano,
War, and Innovation”***

**October/November 2018**

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# Connections to Chemistry Concepts

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| **Chemistry Concept** | **Connection to Chemistry Curriculum** |
| **Le Châtelier’s principle** | The synthesis of ammonia from nitrogen and hydrogen gases is the classic example of Le Châtelier’s principle, and this article explains the principle using examples of temperature, pressure, and concentrations. |
| **Reversible reaction** | The Haber-Bosch synthesis of ammonia highlighted in this article is commonly used to teach students about reversible reactions. Examples of conditions causing this reaction to favor forward or reverse reactions are discussed. |
| **Exothermic processes** | The concept of an exothermic reaction (negative ΔH) is explained in the article and is connected to Le Châtelier’s principle. The chemical equation for the synthesis of ammonia is included with energy indicated as ΔH° = -92 kJ/mol. |
| **Catalysts** | The importance of catalysts in chemical reactions is highlighted in the Haber-Bosch synthesis of ammonia article. Iron is mentioned as the catalyst used, and a potential energy diagram for a catalyzed versus uncatalyzed reaction is featured in Figure 4 of the article. |
| **Lewis electron-dot structures** | The Haber-Bosch reaction is illustrated in Figure 2 of the article with Lewis electron dot structures that clearly show the triple bond in the N2 molecule. |
| **Multiple covalent bonds** | The article describes the triple covalent bond in the nitrogen molecule as “incredibly strong” “and almost unreactive”. The triple bond is illustrated with a Lewis electron dot structure in Figure 2. |

# Teaching Strategies and Tools

## Standards

* Links to **Common Core Standards for Reading**:
	+ **ELA-Literacy.RST.9-10.1:** Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.
	+ **ELA-Literacy.RST.9-10.5**: Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).
	+ **ELA-Literacy.RST.11-12.1**:Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.
	+ **ELA-Literacy.RST.11-12.4:**  Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.
* Links to **Common Core Standards for Writing**:
	+ **ELA-Literacy.WHST.9-10.2F**: Provide a concluding statement or section that follows from and supports the information or explanation presented (e.g., articulating implications or the significance of the topic).
	+ **ELA-Literacy.WHST.11-12.1E**: Provide a concluding statement or section that follows from or supports the argument presented.

## Vocabulary

* **Vocabulary** and **concepts** that are reinforced in the October/November 2018 issue:

Food chemistry

Structural formulas

Chemical reactions

Reaction rates

Oxidation & reduction

Distillation

Environmental chemistry

* Consider asking students to read “Open for Discussion: The Human Drive to Explore Space” to learn about the risks of space exploration prior to reading the article “Mars vs. Titan: A Showdown of Human Habitability.”
* Students may become interested in growing crystals to connect chemistry and art after reading the articles on pages 2 and 19.
* To help students engage with the text, ask students which article **engaged** them most and why, or what **questions** they still have about the articles, and what they would like to explore further.
* Ask students if they have questions about some of the issues discussed in the articles.
* The *ChemMatters* Teacher’s Guide has suggestions for further research and activities.

# Possible Student Misconceptions

1. **“Natural (organic) fertilizers are better than chemical (man-made) fertilizers”** Plants cannot distinguish whether the nitrogen they use for growth and making plant proteins comes from a natural or a man-made source. So, nitrogen is nitrogen, regardless of its origin. Natural fertilizers often have smaller concentrations of the nitrogen, phosphorous, and potassium (N-P-K) that plants require, and some natural fertilizers may not contain all three of these macronutrients. Chemical fertilizers are typically more concentrated and contain all three of the macronutrients (N-P-K). They, also, are more easily transported than bulk natural fertilizers such as animal waste (manure), dead organisms, or compost. Some benefits of natural fertilizers are that they recycle materials that are considered wastes, they add compost and organic matter to the soil, and they depend on microorganisms to slowly decompose them so they are less likely to “burn”, or overfertilize plants. Chemical fertilizers have the advantages of being easy to transport and apply, generally less expensive (if a person must purchase fertilizer), and have consistent concentrations and quality.
2. **“When a chemical reaction has reached equilibrium, the concentration of reactants and products are equal, and the reaction stops.”** A chemical reaction at a specific set of equilibrium conditions does not stop, although the relative ratios of products and reactants are constant. At equilibrium, the *rate* of the forward reaction and formation of products is equal to the *rate* of reverse reaction and the re-formation of the reactants. The concentrations of the products and reactants are rarely equal. An analogy might be a student jogging on a treadmill. If the rate of the student running forward and the rate of the treadmill belt moving backward are equal, then the student’s position on the treadmill doesn’t change, even though the student is still actively running (not standing still). The runner is in equilibrium with the treadmill (rate forward = rate reverse). Considering “concentrations” in this analogy, the student may be at the midpoint along the length of the treadmill belt, but that student could also be closer to the front, or closer to the back and still be in equilibrium, as long as the student’s position doesn’t change on the belt. Equilibrium reactions appear to stop because there is no net change in concentrations of reactants or products at that set of conditions, but the reaction is still occurring—just like the runner continues to run on the treadmill.
3. **“Man-made fertilizers are not needed to produce food for the world because plant growth is a natural process.”** In 2002, it was estimated that 40% of the world’s seven billion people were kept alive with food grown using chemical fertilizers. (<http://home.cc.umanitoba.ca/~vsmil/pdf_pubs/Nitrogen%20and%20Food%20Production.pdf>) Some plants, called legumes, have a symbiotic relationship with nitrogen-fixing bacteria that allow them to “produce” the nitrogen they need to grow. A few carnivorous plants (e.g., the Venus flytrap) supplement their nitrogen requirements by digesting small insects. However, most plants must absorb nitrogen through the soil and are dependent on the nitrogen cycle to supply this critical element. Without chemical fertilizers, the food produced by the processes of natural plant growth would not be capable of sustaining the seven billion inhabitants presently on earth—much less the estimated 10 billion people by 2050.
4. **“Are ‘chemical equilibrium’ and ‘steady state’ the same thing?”** They are similar in some respects, but they are not identical. A steady state has (a) conditions that are stable within the system, (b) a constant input of energy to maintain the steady state, and (c) a higher state of entropy (disorder) than its surroundings due to the constant flow of energy into the system. A chemical equilibrium has (a) conditions stable within the system, (b) no net energy entering or leaving the system, and (c) a reduction in entropy between the system and the environment. For example, in order for a student to maintain a constant body temperature of 37°C (a steady state), the student must generate body heat from digesting food (constant input of energy), or the body temperature falls. A chemical equilibrium exists in an unopened bottle of sparkling (carbonated) water at a constant temperature. The carbon dioxide gas in the space between the bottle cap and the water contains pressurized CO2 and there is dissolved CO2 in the fizzy water. The CO2 gas is in constant movement between the gas space and the liquid, representing a chemical equilibrium that does not require external energy to maintain the constant exchange.

# Anticipating Student Questions

1. **“Why don’t plants obtain the nitrogen that they need from the air?”** While the earth’s atmosphere contains about 78% nitrogen by volume, plants are unable to directly use the atmospheric nitrogen, N2, for growth. Atmospheric nitrogen is a diatomic molecule with the two nitrogen atoms bonded together with a triple covalent bond requiring a bond-dissociation energy of 946 kJ/mol—about double that of molecular oxygen containing a double bond. This high bond strength makes N2 highly unreactive. So atmospheric nitrogen (N2) must be “fixed”, or converted into a more useful form, in order for plants to be able to use the nitrogen for growth. This nitrogen fixation process is accomplished through the nitrogen cycle. The nitrogen cycle has a biological component, where bacteria convert N2 into plant-friendly nitrates or ammonia in the soil. There is also a non-biological nitrogen fixation process when lightening converts atmospheric nitrogen into nitrogen oxides that can form plant-friendly nitrogen compounds.

([*https://www.britannica.com/science/nitrogen-cycle*](https://www.britannica.com/science/nitrogen-cycle))

1. **“How many people could live on Earth if man-made chemical fertilizers were not available?”** This is a complex question because it involves social issues such as life styles as well as biophysical factors including fertilizers, water, and energy. For example, more people could live on the earth if wealthier people and nations reduced or eliminated their consumption of meats. In 1798, Thomas Malthus predicted in his book, *An Essay on the Principle of Population*,that famine was imminent because the world’s population (about one billion people) had surpassed Earth’s carrying capacity, the maximum population of a species that can survive indefinitely in that environment. Thankfully, he was incorrect because he was unable to predict many crucial factors including the discovery of the Haber-Bosch process. In 1997, the Canadian geographer Vaclav Smil calculated that the carrying capacity of the earth would be about four billion people without the industrial fixation of nitrogen (Haber-Bosch process). Some estimates of the “organic” carrying capacity of the earth (without the use of chemical fertilizers) are as low as 2.4 billion people. (<http://agrpartners.com/wp-content/uploads/2013/09/AGR-Thought-Piece-Carrying-Capacity1.pdf>) By any estimate, the world’s population would be much smaller without the availability and use of chemical fertilizers.
2. **“How do plants use the three macronutrients nitrogen, phosphorous, and potassium?”** Plants need 17 essential elements to successfully grow. The “Big 3”, or macronutrients, are nitrogen, phosphorous, and potassium. Nitrogen is needed by plants to make proteins for enzymes and structural growth, and it is critical in producing the chlorophyll used in photosynthesis. Because of these functions, nitrogen is often considered the most important nutrient. Phosphorous is vital for using and storing energy (think ATP) in plants. Famers and gardeners often use a superphosphate fertilizer on plants because it is linked to abundant flower and seed/fruit production. Also, phosphorous is used in forming DNA. Potassium’s use in plants is more indirect, but still important. Potassium is associated with disease resistance and overall plant quality. Potassium is required for the activation of over 80 enzymes needed throughout plants.
3. **“Can fertilizers explode like a bomb?”**Nitrogen compounds are typically found in many explosives such as dynamite, or trinitrotoluene (TNT). However, chemical fertilizers like the ones you would purchase at a garden store such as 10-10-10 do not have a high enough concentration of nitrogen compounds to explode. Even higher concentrations of commercial fertilizers such as 30-30-30 don’t explode. However, a common and inexpensive ingredient used in some commercial fertilizers, ammonium nitrate, under the wrong conditions has been involved in some explosions. A 2013 explosion at the ammonium nitrate fertilizer plant in West, Texas, killed 15 people and injured many more. Another explosion at a dock in Texas City, Texas, in 1947 is considered one of the worst industrial accidents in U.S. history. A fire onboard the docked ship *SS Grandchamp* carrying 2,200 tons of ammonium nitrate caused a massive explosion which killed at least 581 people, injured more than 5,000, and destroyed about 1,000 buildings on the land. So, commonly available chemical fertilizers cannot explode like a bomb.
4. **“Why do people talk about “fixing” nitrogen when the nitrogen molecule needs to be broken apart and not put together?”**It does seem like a contradiction! In order for nitrogen to be in a useful form for plants, the relatively unreactive atmospheric nitrogen molecule must be converted or “fixed” into a more soluble compound. The term fixed is used in a sense similar to people saying that they are going to fix, or prepare, breakfast. It is certainly not using the term in the way you may say that you are going to fix (repair) your skateboard. So, the word fix, may have several uses in our language, and in the case of nitrogen, it means the nitrogen will be chemically converted to a useful form for plant.

# Activities

**Labs and demos**

 **“Le Châtelier’s Soda” lab:** This American Association of Chemistry Teachers (AACT) lab (noted as AP level, but might be appropriate for other high school students) uses club soda and dry ice as a variation on the common cobalt(II) chloride activity to study how an equilibrium reaction is affected by changes in pressure, temperature, and concentration. Resources provided include the Teacher Guide, Student Activity, and Answer Key with references to the AP Curriculum Framework and NGSS. (Access is restricted to AACT members, but the article will be available for free until December 1, 2018 at <https://teachchemistry.org/classroom-resources/le-chatelier-s-soda>.)

**“Iodine Clock Reaction: A Study of the Effects of Concentration, Temperature, and a Catalyst on Reaction Rate”:** This lab from Flinn Scientific provides teacher information on conducting the activity, including sections on Materials, Safety Precautions, Preparation, Procedure, Disposal, Results and Discussion, and NGSS Alignment. (<https://www.flinnsci.com/api/library/Download/513df678faef4d5dad2c85eb789be1d9>)

**Simulations**

“**Reversible Reactions” (PhET):** Students can vary temperature, activation energy, and concentration, as reaction results are displayed in either species-formation or energy histograms. Additional teacher-submitted activities to accompany the simulation are provided. (<https://phet.colorado.edu/en/simulation/reversible-reactions>)

**“Reactions and Rates” (PhET):** This simulation provides students the opportunity to explore reactions by colliding reactant particles and designing experiments using different reactions, concentrations, and temperatures, as well as studying reversible reactions and factors affecting reaction rates. Additional teacher-submitted activities to accompany the simulation are available. (<https://phet.colorado.edu/en/simulation/legacy/reactions-and-rates>)

**Media**

**“The Chemical Reaction That Feeds the World—Daniel D. Dulek”, video (5:18):**  This TED-ED video clip (with a link to support material) explains with pictures and animations the importance of the Haber process in feeding the world through the production of ammonia. (<https://www.youtube.com/watch?v=o1_D4FscMnU>)

**“The Father of Poison Gas—Fritz Haber”, video (5:46):**  This video, part of the “Who Did What in WW1?” series, describes the work of Haber—both in saving lives through the production of fertilizers, and in killing soldiers through the production and use of chlorine and other poison gases. (<https://www.youtube.com/watch?v=ztzKHU2oaF8>)

**Lessons and lesson plans**

**“Catalysis and Catalytic Converters”:** This AACT 5Es high school lesson plan (with teacher and student instructions) introduces catalysts and reinforces stoichiometry and chemical reactions in an inquiry-based activity with possible student extensions. A teacher demonstration opens the activity before students investigate the decomposition of hydrogen peroxide. (Access is restricted to AACT members, but will be available for free until December 1, 2018 at <https://teachchemistry.org/classroom-resources/catalysis-catalytic-converters>.

**“All Things Being Equal!” lessons:** This is a set of three guided-inquiry lessons to help students correct misconceptions about equilibrium, predict changes using Le Châtelier’s principle, and use the value of the equilibrium constant to predict the extent of reactants and products. The three lessons (two activities and one lab, requiring about 35–45 minutes each are provided as a Teacher Guide with materials needed and preparation information (<http://static.nsta.org/connections/highschool/201210AllThingsBeingEqualTeachersGuide.pdf>); student materials are available at <https://www.gvsu.edu/targetinquiry/tidocuments-home.htm> but require a free registration to access them.

**Projects and extension activities**

**Establish and monitor a classroom aquarium to study nitrogen fixation and the nitrogen cycle:** A balanced aquarium (whether it is freshwater or saltwater) requires nitrogen fixation and a functioning nitrogen cycle in the tank to maintain habitable conditions for the marine organisms. Students could research the process for establishing a new aquarium; study the components and chemistry of the applicable biological nitrogen cycle; test nitrates, nitrites, ammonia, and pH levels in the aquarium with test kits; and monitor the health of the marine organisms (fish, moon jellyfish, aquatic plants) as a function of water quality.

**“Le Châtelier’s Principle and the Solubility of Carbon Dioxide” lab:** Students can apply the concept of Le Châtelier’s principle to this Flinn Scientific lab activity which uses the concepts of gas solubility, Boyle’s law, pH, and acid-base indicators as an extension of more traditional Le Châtelier’s principle activities. Seltzer (carbonated) water is studied in a 10-mL syringe to observe the changes of pressure and temperature on the carbonated water. (<https://www.flinnsci.ca/api/library/Download/b7512bb8f8b445f9938df114a188d88e>) A teacher video by the same title (12:54) demonstrates this lab activity (or possible teacher demonstration) at <https://www.youtube.com/watch?v=QtCRxvCxa6M>.

# References

**The references below can be found on the *ChemMatters* 30-year DVD, which includes all articles published from the magazine’s inception in October 1983 through April 2013; all**

**available Teacher’s Guides, beginning February 1990; and 12 *ChemMatters* videos. The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [***http://ww.acs.org/chemmatters***](http://www.acs.org/chemmatters)**. Click on the “Teacher’s Guide” tab to the left, directly under the “*ChemMatters Online"* logo and, on the new page, click on “Get 30 Years of *ChemMatters* Magazine!” (the icon on the right of the screen).**

**Selected articles and the complete set of Teacher’s Guides for all issues from the past three years are available free online at the same Web site, above. Click on the “Issues” tab just below the logo, *“ChemMatters Online”*.**

In “Aquarium Chemistry: Life in the Balance”, author Ruth writes about nitrogen chemistry (the nitrogen cycle) in maintaining the water quality for organisms in an aquarium. Ruth discusses the role of ammonia, nitrates, and nitrites, as well as other chemical factors in maintaining a healthy aquarium. (Ruth, L. Aquarium Chemistry: Life in the Balance. *ChemMatters*. 2002, *20* (1), pp 6–7)

The Teacher’s Guide for the February 2002 *ChemMatters* Ruth article above provides additional information on the ammonia/ammonium equilibria and the connection to pH, including an application of Le Châtelier’s principle.

“What’s So Equal About Equilibrium?” discusses chemical equilibrium and provides analogies and examples of equilibria from everyday life. The formation of ammonia is discussed as an example of Le Châtelier’s principle. (Tinnesand, M. What’s So Equal About Equilibrium? *ChemMatters*. 2005, *23* (3), pp 11–13)

The Teacher’s Guide for Tinnesand’s September 2005 *ChemMatters* article above contains additional information about ammonia synthesis, equilibrium, Le Châtelier’s principle, and Fritz Haber. An activity, “The Equilibrium Game”, is described for use with pairs of students.

 In “Nitrogen from Fertilizers: Too Much of a Good Thing”, fertilizers and the nitrogen cycle are discussed and diagrammed, along with a look at possible damage to the environment from excess fertilizers. Sidebars on “Organic Farming” and “Haber-Bosch Process: Chemistry that Changed the Way We Farm” provide additional information for consideration. (Nolte, B. Nitrogen from Fertilizers: Too Much of a Good Thing. *ChemMatters*. 2010, *28* (2), pp 5–7)

 The Teacher’s Guide for the 2010 *ChemMatters* Nolte article provides more information on nitrogen and its compounds, the nitrogen cycle, ammonia, fertilizers, and nitrogen pollution. Suggestions for additional lessons, demonstrations, and student projects are included.

 “Tooth Decay: A Delicate Balance” contains a large schematic representation of chemical equilibrium using balance pans filled with items to clarify equilibrium, how it changes, and how it is re-established. The article also includes descriptions of equilibria involving mineralization/demineralization of teeth and carbonic acid/bicarbonate chemistry influencing pH. (Warmflash, D. Tooth Decay: A Delicate Balance. *ChemMatters*. 2015, *33* (3), pp 8–10)

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 This *JCE Classroom Activity* allows students to cheaply and quickly investigate Gibbs free energy and the effect of stresses on equilibria, using rubber bands. (Hirsch, W. Rubber Bands, Free Energy, and Le Châtelier’s Principle. *J. Chem. Educ.*, 2002, *79* (2), pp 200A–200B; https://pubs.acs.org/doi/pdf/10.1021/ed079p200A. Note that this link takes you to a brief abstract only; the full article is only available to American Chemical Society members or subscribers to the journal.)

 High School teachers’ misconceptions regarding the application of Le Châtelier’s principle and the equilibrium law reduce their ability to explain chemical equilibrium to their students, and this article analyzes the misconceptions and the implications. (Cheung, D. The Adverse Effects of Le Châtelier’s Principle on Teacher Understanding of Chemical Equilibrium. *J. Chem. Educ.*, 2009, *86* (4), pp 514–518; https://pubs.acs.org/doi/pdf/10.1021/ed086p514. Note that this link takes you to a brief abstract only; the full article is only available to American Chemical Society members or subscribers to the journal.)

 This article is a short biography of the controversial Fritz Haber as a scientist, war criminal, family man, and scientific colleague. The special report continues with a storyline of “Chemical Weapons Then and Now.” (Everts, S. Who Was Fritz Haber? *Chem. Eng. News*, 2015, *93* (8), pp 18–21; https://pubs.acs.org/doi/10.1021/cen-09308-cover2. Note that this link takes you to a brief abstract only; the full article is only available to American Chemical Society members or subscribers to the journal.)

# Web Resources for More Information

**Fritz Haber**

 This short biography of Fritz Haber provides readers with information on his life-giving work on synthesizing ammonia for fertilizer and his deadly work with poison gas warfare.

(<https://www.smithsonianmag.com/history/fritz-habers-experiments-in-life-and-death-114161301/>)

 For an audio biography (29:00) of Haber, listen to “the Chemist of Life and Death” from the British Broadcasting Corporation.

(<https://www.bbc.co.uk/radio/play/b01062gy>)

**Carl Bosch**

This site provides biographical information on the life and work of Carl Bosch.

(<https://www.thefamouspeople.com/profiles/carl-bosch-7250.php>)

**Haber-Bosch process**

The history of the discovery of the Haber-Bosch process for producing ammonia and the impact on feeding the world is explained in this Web article.

(<https://www.thechemicalengineer.com/features/cewctw-fritz-haber-and-carl-bosch-feed-the-world/>)

 Read this article to learn more about how the Haber-Bosch process of ammonia synthesis has changed the world.

 (<https://www.researchgate.net/publication/248828433_How_a_century_of_ammonia_synthesis_changed_the_world>)

**Ammonia**

This article looks at the global uses, annual production, and manufacture of ammonia.

(<http://www.essentialchemicalindustry.org/chemicals/ammonia.html>)

 This video (2:59) shows one of Haber-Bosch’s original ammonia factories and then, through animation, explains how pure hydrogen is produced and converted into ammonia.

 (<https://www.youtube.com/watch?v=uMkzxV_y7tY>)

**Le Châtelier’s principle**

This site provides an explanation of Le Châtelier’s principle with equations, and it provides examples of changes to the equilibrium from common variables.

(<https://www.chemguide.co.uk/physical/equilibria/lechatelier.html>)

Khan Academy provides this video (14:42) explanation of Le Châtelier’s principle, plus additional videos and practice.

(<https://www.khanacademy.org/science/chemistry/chemical-equilibrium/factors-that-affect-chemical-equilibrium/v/le-chatelier-s-principle>)

**Energy changes and reversible reactions**

 Students can review the energy changes in chemical reactions and reversible reactions and their application to ammonia synthesis at this site.

(<http://www.bbc.co.uk/schools/gcsebitesize/science/add_aqa_pre_2011/chemreac/energychangesrev3.shtml>)

**The Guano War**

 For more information on the history of the Guano War and its importance for the Western world, visit this link.

 (<https://www.atlasobscura.com/articles/when-the-western-world-ran-on-guano>)

 This site provides pictures of the guano trade on the Chincha Islands where the Guano War took place.

 (<http://americanhistory.si.edu/norie-atlas/guano-trade>)

**Carrying capacity of Earth**

 Readers can find charts and additional information on food production and world population as a result of using synthetic fertilizers at this site.

 (<https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed>)

 This article shows that food production from the Haber-Bosch process is only one of the factors determining the ultimate number of people who can live on Earth.

 (<http://www.bbc.com/earth/story/20160311-how-many-people-can-our-planet-really-support>)