ISEP Interdisciplinary Science and Engineering Partnership

Magnets and Dominoes: A Simple Mechanics Analogy for Chemical Bonding

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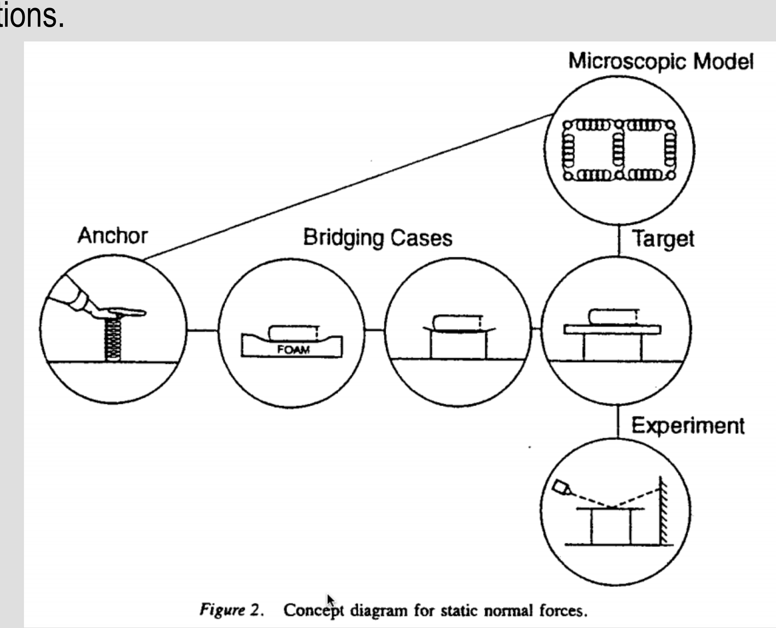
Abstract

We present a common interdisciplinary misconception underlying chemical bonding energetics and review the associated literature. We present and describe a self-invented simple series of mechanical work activities making use of common ceramic CB60 magnets and everyday dominoes that we believe provides an insightful kinesthetic analogy leading to appropriately sophisticated insights into chemical bonding for introductory college students who have taken work and energy in introductory physics. Suggestions for how to use the activity in the class are included.

Background

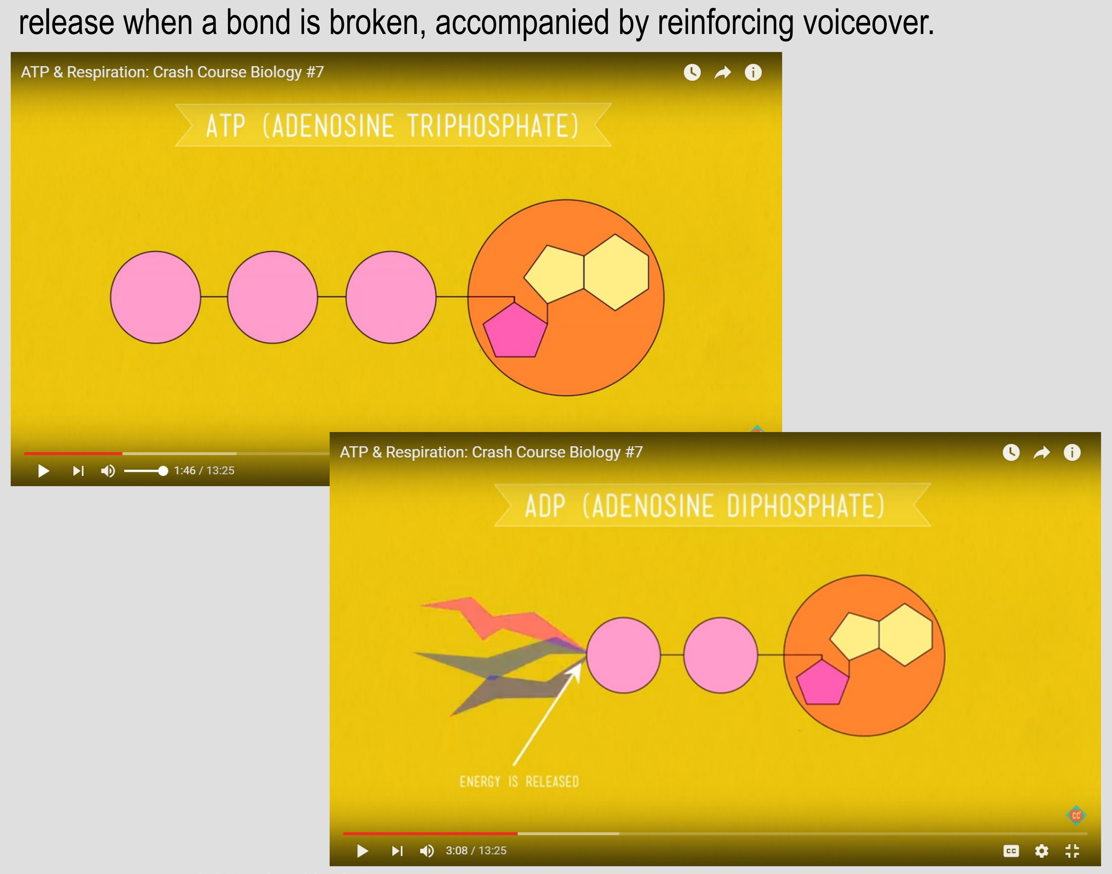
We are seeking to develop a concrete kinesthetic ***bridging analogy*** after Clement (1993) in an attempt to foster student use of sophisticated analogous models that are accessible to students -- explicitly using anchoring intuitions, structural chains of analogous reasoning and mechanistic models in lessons. A famous example of a bridging analogy is the use of a set of intermediate cases to learn about the normal force in introductory mechanics. To learn about normal forces supporting a book on a table, Clement (1993) advocates the use of a sheet of compressible soft foam, and then a thin flexible piece of wood (a meter stick), leading to microscopic spring models that can be tested via laser deflections.



Clement, 1993

In our investigation we are developing a bridging analogy to address a widely- held and propagated error about the nature of chemical bonding, specifically that energy is released when bonds are broken. Papers by Dreyfus, Sawtelle, Turpen, Gouvea, and Redish (2014), and Galley (2004) specifically report on this misconception, with Galley discussing interventions appropriate for biology and medical students, while Dreyfus et al term the misconception as requiring ***Interdisciplinary Reconciliation*** – the idea that energy conceptual portraits and descriptions in Physics Biology and Chemistry conflict and promote such misconceptions.

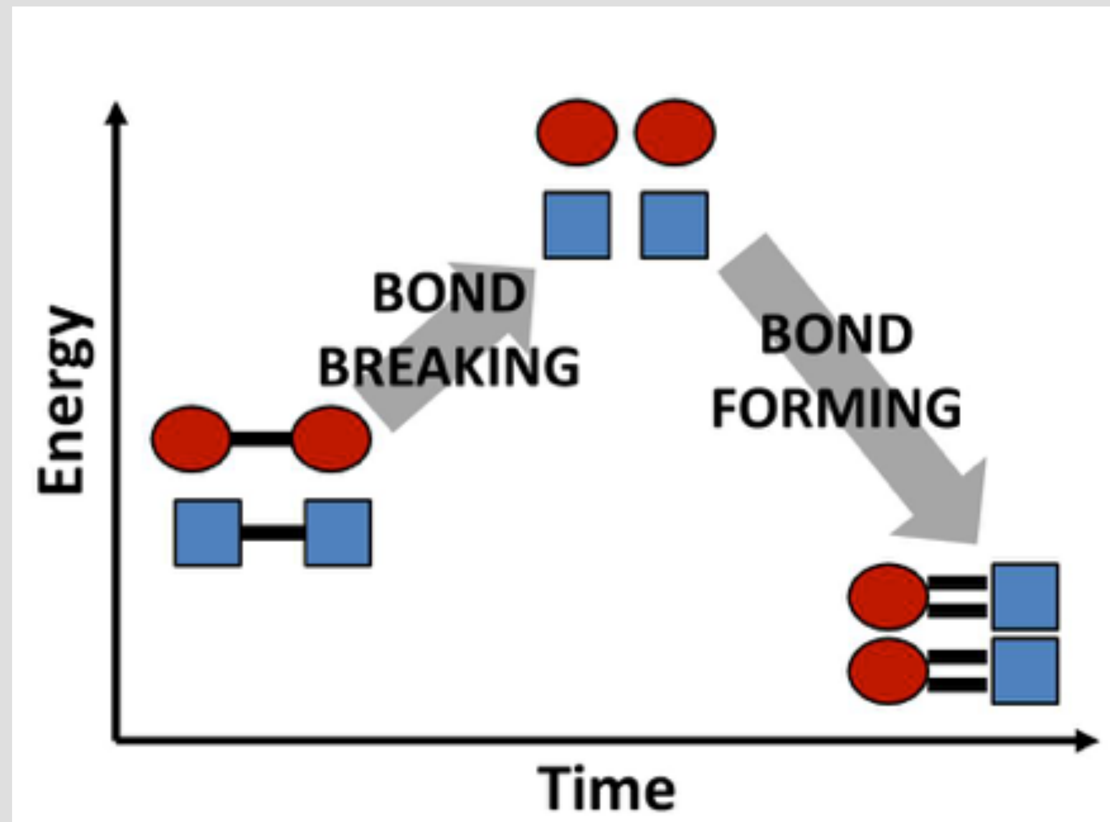
Below is a visual example of this malapropism from a well-known and widely viewed YouTube science video series.
"*ATP and Respiration: Crash Course Biology Lesson #7*" schematically shows an ATP molecule which has a phosphate group broken off leaving ADP, with the site of the broken bond shooting out lightning bolts representing energy release when a bond is broken, accompanied by reinforcing voiceover.



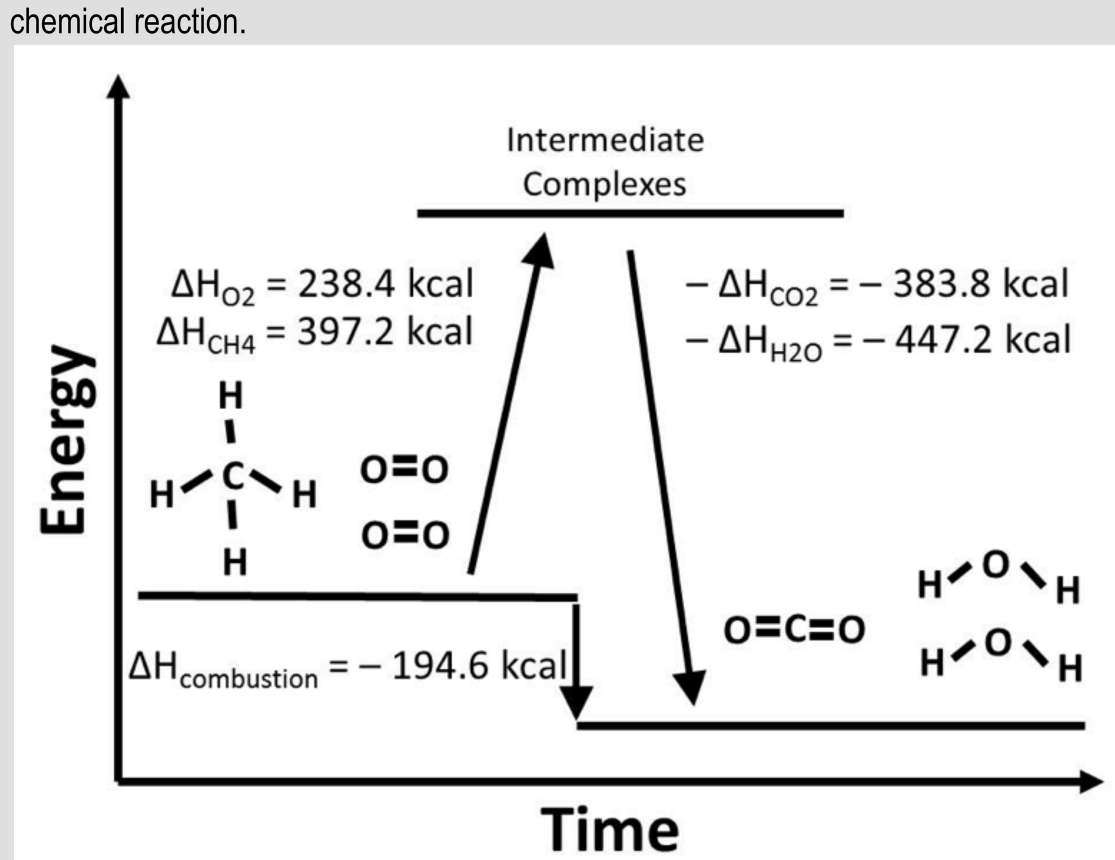
www.youtube.com/v/00jbG_cfGuQ

A Correct Bonding Energetics Example: Burning Methane

A highly simplified representation of the bonding process for an exothermic (energy releasing) chemical reaction. For ***all*** chemical reactions energy is required to break a chemical bond; later energy is released when a new bond is formed.



In a more complete description, the heat of combustion of methane ($\Delta H_{combustion}$) is represented in terms of approximate total bond energies for the reactants and products. The calculated quantities for the total bond energies come from Sanderson's per mole calculations multiplied by the coefficients in the balanced chemical equation for the combustion of methane. Negative energy values signify that energy is released, and positive energy values signify that energy is absorbed. While the combustion of one mole of methane results in the release of 195 kcal of energy, this exothermic reaction is the combination of endothermic bond breaking and exothermic bond formation. Intermediate complexes are not shown for simplicity due to the fact that a large variety of intermediate complexes are formed during the chemical reaction.



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Bond energy of CH_4 = 397.2 kcal/mol	Bond energy of CO_2 = 383.8 kcal/mol
Bond energy of O_2 = 119.2 kcal/mol	Bond energy of H_2O = 223.6 kcal/mol

$$Total\ Bond\ Breaking\ Energy = \Delta H_{CH4} + 2\Delta H_{O2}$$

$$Total\ Bond\ Breaking\ Energy = (1\ mol)\left(397.2\frac{kcal}{mol}\right) + (2\ mol)\left(119.2\frac{kcal}{mol}\right)$$

$$Total\ Bond\ Breaking\ Energy = 397.2\ kcal + 238.4\ kcal = \underline{\mathbf{635.6\ kcal}}$$

$$Total\ Bond\ Forming\ Energy = -\Delta H_{CO2} + (-2\Delta H_{H2O})$$

$$Total\ Bond\ Forming\ Energy = -(1\ mol)\left(383.8\frac{kcal}{mol}\right) - (2\ mol)\left(223.6\frac{kcal}{mol}\right)$$

$$Total\ Bond\ Forming\ Energy = -383.8\ kcal - 447.2\ kcal = \underline{\mathbf{-831.0\ kcal}}$$

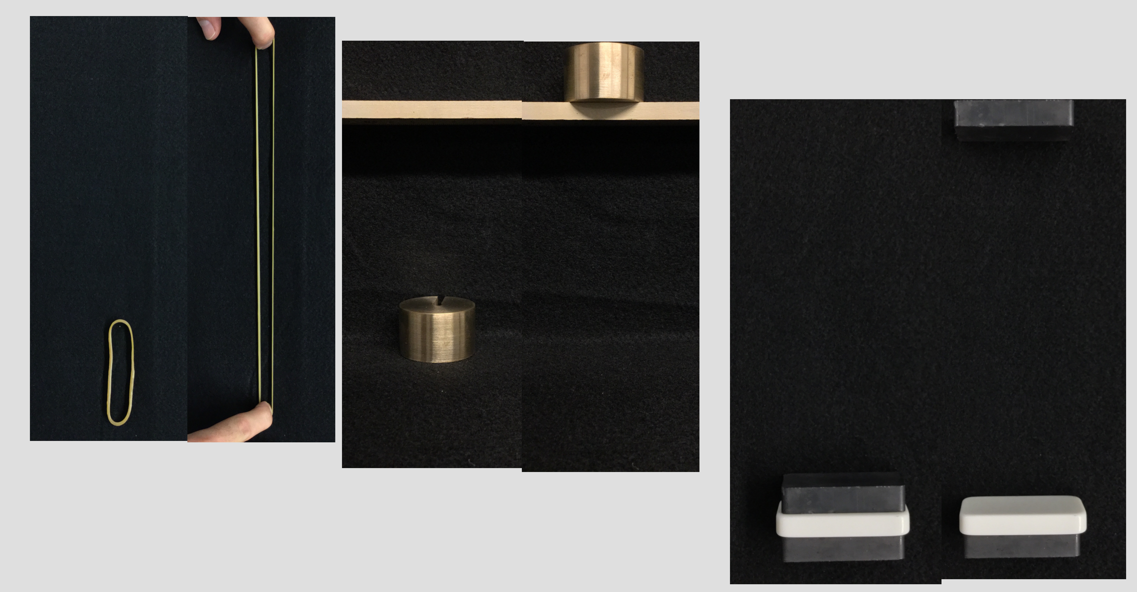
$$\Delta H_{combustion} = Total\ Bonding\ Breaking\ Energy + Total\ Bond\ Forming\ Energy$$

$$\Delta H_{combustion} = 635.6\ kcal - 831.0\ kcal = \underline{\mathbf{-194.6\ kcal}}$$

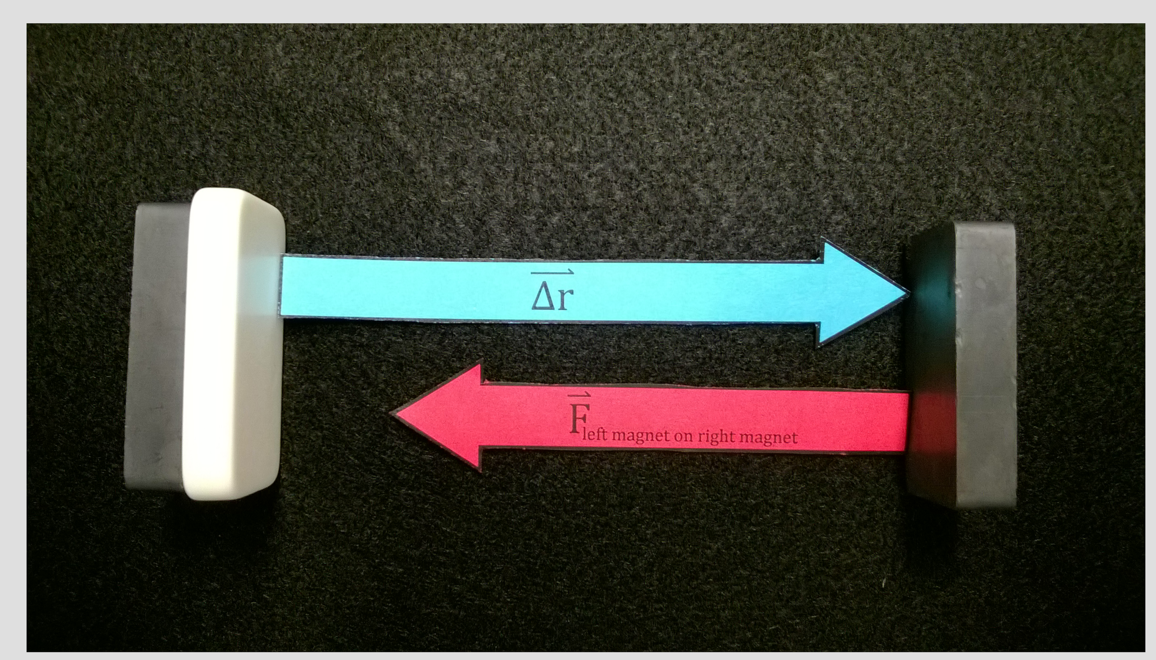
Figure 5. Calculations completed by Dr. Sanderson (1968) for the bond energies of methane, oxygen, carbon dioxide, and water for the combustion of methane.

Magnets and dominoes: Our kinesthetic bridging analogy

Our analogy follows the Physics and Everyday Thinking (Goldberg, Robinson & Otero, 2008) sequence for energy storage. Goldberg et al start with wheeled carts colliding with rubber bands and extend student activity examining energy transformations via gravitational forces, electrostatic and magnetic forces. We focus on the idea that **transforming energy from kinetic to potential forms requires some external force acting upon an object which is displaced a direction opposite to the internal force** of elastic deformation, gravitational attraction, electrostatic or magnetic attraction or repulsion. This invokes the textbook standard work-energy theorem widely taught in introductory physics, and extends it to a series of different potential energies. We like to note that in German potential energy is referred to as configuration energy, neatly sidestepping conceptual confusion like "potential for energy or energy"?

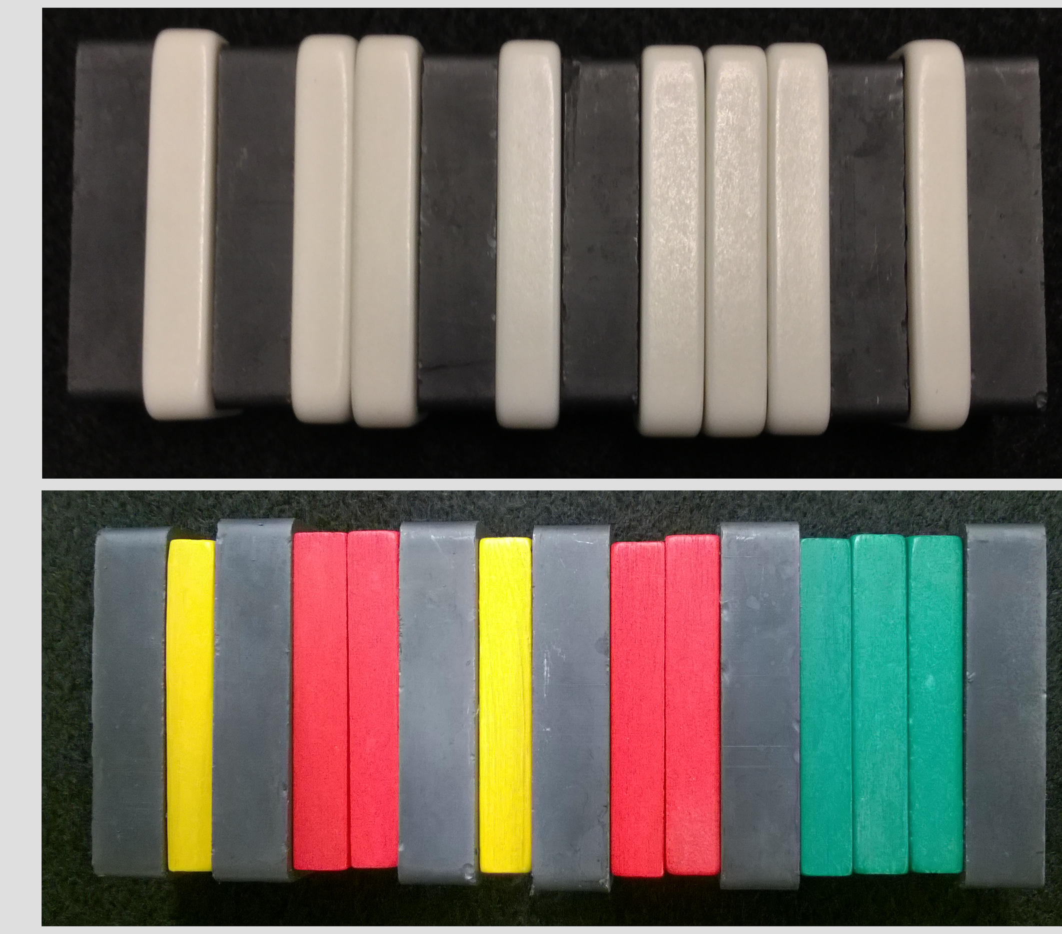


Potential energy increased by stretching rubber bands, lifting an object with mass in a gravitational field and separating two magnets that are attracting one another.



Farther separation of magnets represents weaker bonds with greater configuration or potential energy. Below are four bonds, each one weaker than the one before and each storing more energy than the one before. Individual dominoes represent a "dollop" of bond energy; more dominoes means more energy associated with a bond.

Separating weaker bonds requires less bond breaking energy be put into the reactants; a student can feel themselves using less force and doing less work when separating weak bonds. Forming new bonds a student can feel the magnet exerting more force on their hands when pulling into a tighter bond. Once can qualitatively feel stronger and weaker forces separating and recombining magnets. The difference in the work required to break and make bonds produces the net energy of reaction. Kinesthetically manipulating concrete artifacts provides the analogy.
Breaking a bond ALWAYS requires energy.
Creating a new bond ALWAYS releases energy.



Possible linear models of a complex compound like a hydrocarbon. Colored "tipping" dominoes are available, so bond strength can be color-coded like math manipulatives.

Discussion

Likely curricular adaptations could include telling a chemical story while acting out bond breaking and bind making using magnets and dominoes like puppets. For example in photosynthesis carbon is first fixed by breaking tightly bonded CO_2 using solar energy; complex hydrocarbons store some of this solar energy in their new weaker bonds, O_2 is discarded. Burning wood or metabolic respiration of sugars break the weak complex hydrocarbon bonds, reintroduce oxygen and re-form the strong tight bonds of CO_2 in the carbon cycle. Similar stories can be told for the production and oxidation of fuels or explosives, smelting and oxidizing pure metals (as common metal objects or as plates in batteries) and so forth. *The idea is to unite introductory mechanics work, energy and chemical bonds in some meaningful way, while emphasizing that chemical reactions are multi-step processes beginning with bond breaking and ending with bond formation.*

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