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Interactive Learning Tools to Visualize Chemistry and its Connections

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Abstract: Open access, peer-reviewed interactive learning tools for the education community to see and understand why isotopes matter, the science of climate change, planetary boundaries, and the responsible practice of chemistry.

Keywords: Climate change · Isotopes · Planetary boundaries · Responsible chemistry · Sustainability · Visualization

1. Seeing and Understanding

In chemistry classrooms and laboratories, learning has been transformed by visualizations that support students in creating mental models and images of molecules and atoms combining in chemical change and in translating squiggles of instrumental data into structural meaning. Equally important is helping students see and understand the complex systems that underlie global challenges and visualize how knowledge of chemistry can contribute to solutions. Similarly, across the spectrum of the sciences, a parallel visualization revolution has helped researchers see and understand new phenomena that are hard to comprehend because the objects of study are too far away (astronomy), unrelatable to everyday experience (quantum physics), too small (chemistry), or too complex (climate science).

Over the past 20 years, teams of undergraduate students and faculty at the King's Centre for Visualization in Science (KCVS)[1] at the King's University in Edmonton, AB, Canada have tapped the power of interactive electronic visualizations to create learning tools that support the global chemistry education community in seeing and understanding the molecular world. Recently, KCVS has focused on visualizing the complex systems that connect knowledge of chemistry to global sustainability challenges such as climate change. We highlight here four visualization initiatives created in partnership with International Union of Pure & Applied Chemistry (IUPAC) project task groups of global science and education experts. For each initiative, we describe key interactive visualization tools and references for educators wanting to incorporate these interactive learning tools into their classrooms. Some 500,000 users from over one hundred countries access these and other interactive KCVS visualizations each year.

2. Visualizing Why Isotopes Matter

Most chemistry students at the secondary and tertiary levels are familiar with radioactive isotopes, and all will have used stable isotope abundances and relative atomic masses of isotopes to calculate the atomic weights of elements. But fewer students are introduced to the importance of mass fractionation processes involving stable isotopes that have led to the realization that atomic weights for many elements are not constants of nature.[2] While this recognition introduces complexity to teaching and learning about the nature of matter, visualizing the variations in isotopic abundances and atomic weights gives valuable insights into almost every field of science and medicine. Examples include answering questions about historic planetary temperature records; determining whether an athlete cheated using doping with testosterone or other hormone samples from exogenous sources; and learning how scientists discover the sources of methane molecules on Mars.[3] Educators can help students understand that isotopes matter!

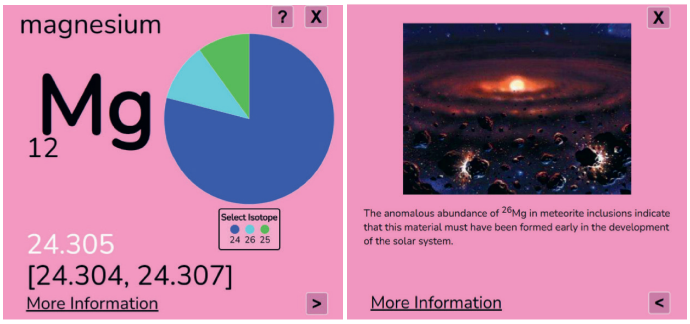

Fig.1. Screen captures of front (1a) and back (1b) of isotope cards for magnesium from *https://Isotopesmatter.com*.

Due to the variation in isotopic abundances for elements from diverse sources, the atomic weights for many elements in IUPAC's periodic tables after 2009 are listed as intervals rather than fixed numbers with uncertainties (Fig. 1a, black lettering). This can lead introductory chemistry students to be confused about which atomic weight numbers to use within a given interval for calculations.

Over several decades, the Commission on Isotopic Abundances and Atomic Weights worked with an IUPAC project team to catalogue over 3000 known stable and radioactive isotopes of all elements, culminating in a comprehensive 293-page scholarly publication and the first paper version of the new IUPAC Periodic Table of the Elements and Isotopes.[4] As a legacy contribution to the 2019 UN International Year of the Periodic Table, KCVS partnered with the IUPAC project team to visualize this rich set of data in an interactive electronic form that is openly accessible to the education community. The website *https://IsotopesMatter.com* provides a comprehensive set of educational resources which includes the IUPAC Interactive Electronic Periodic Table of the Isotopes and Elements (Fig. 2). Users can click on an element and pull up a pie chart showing the different stable isotopes that contribute to the atomic weight of an element (Fig. 1a). Flipping the electronic card over (Fig. 1b) gives an interesting application of isotopes of that element and selecting 'more information' opens a pdf document with a list of all known isotopes of that element and applications of variations in isotopic abundance to industry, earth science, biology, medicine, and forensics. The accompanying educational materials at *https://IsotopesMatter.com* walk through the importance of isotopes, explain the colour scheme for the IUPAC Periodic Table of Isotopes and Elements, provide sample calculations using atomic weight intervals, and end with a forensic case study of how isotopic abundances revealed important information about Ötzi the Iceman, discovered under glacial melt in an Alpine pass on the border between Italy and Austria.

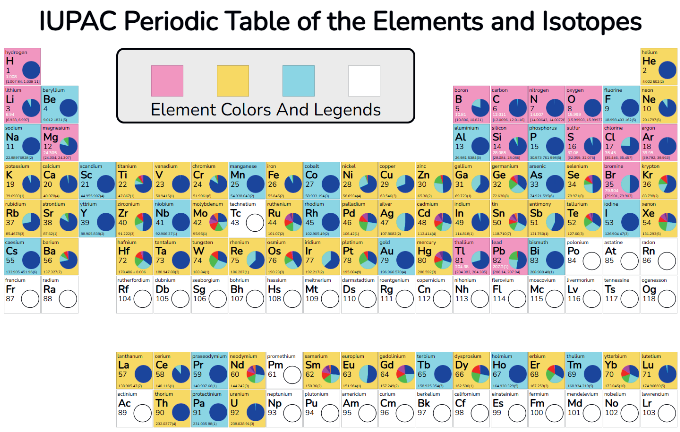

Fig. 2. Interactive IUPAC Periodic Table of the Elements and Isotopes from the KCVS *https://IsotopesMatter.com* website.

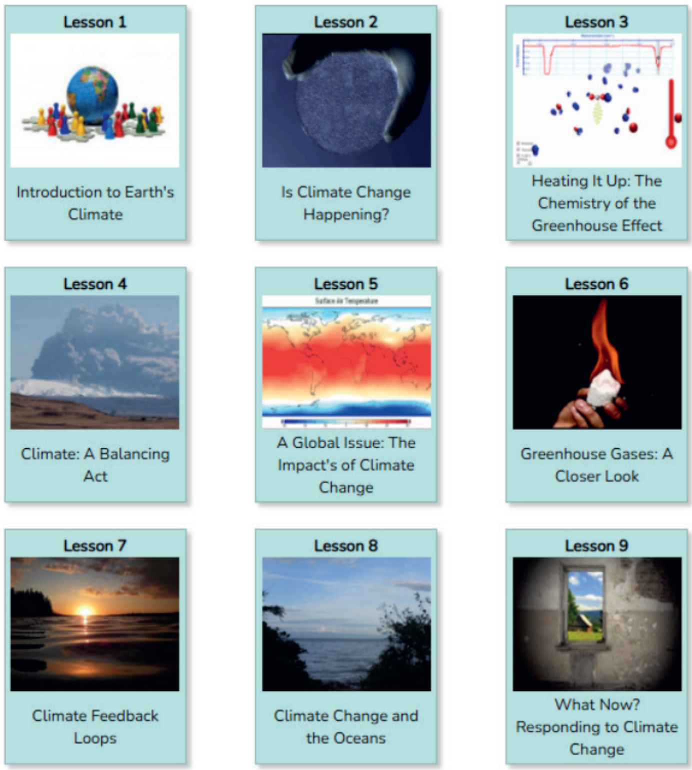

Fig. 3. Screen capture of the *https://ExplainingClimateChange.com* website.

3. Visualizing and Understanding the Science of Climate Change

The website *https://ExplainingClimateChange.com* is a legacy resource for the 2011 UN International Year of Chemistry to support the theme of chemistry's contributions to sustainability, created by a collaboration of the KCVS team with chemists and educators from the Royal Society of Chemistry, the American Chemical Society, IUPAC, and the Federation of African Societies of Chemistry. The KCVS website, which has been regularly updated, guides users through about 50 interactive learning tools embedded in nine lessons, providing a set of comprehensive resources linking climate science to classroom coverage of fundamental chemistry concepts. Users are not told what to think about climate change but given tools to equip them to interrogate data sets and ask good questions about what the data means and how it connects to chemistry. The resource ends with the '*Design our Climate*' simulation[5] that invites users to develop a set of mitigation strategies over five key emission sectors using currently available technology, to bring us closer to achieving net zero.

Building on this resource, KCVS worked with partners at Purdue University and the American Chemical Society to develop the *Visualizing the Chemistry of Climate Change* (*https://VC3Chem.com*) web resources that map the curriculum for foundational chemistry courses onto climate literacy principles, guiding students through exploring how knowledge of gases, isotopes, acids and bases, and thermochemistry can connect to climate literacy (Fig. 3).[6,7]

Finally, undergraduate students in an environmental chemistry course at the King's University have recently curated a set of KCVS climate science resources and provided classroom activities to help their peers and educators connect climate change to cognitive, affective, and kinesthetic learning in chemistry.[8]

4. Visualizing our Planetary Boundaries

The Planetary Boundaries Framework draws on interdisciplinary environmental change research to identify nine central, interconnected Earth system processes that support life on our planet.[9–11] The Planetary Boundaries assess quantitatively, with control variables for each Earth system process, the safe limit for human pressure on these nine processes. As a legacy contribution to the 2022 UN International Year of Basic Sciences for Sustainable Development, KCVS collaborated with an IUPAC project task group focused on systems thinking and sustainability in chemistry[12] and a leading researcher at the Stockholm Resilience Centre to develop the interactive *KCVS Planetary Boundaries Learning Tool*.[13] The learning tool takes a systems approach to help users understand the fundamental role that chemistry plays in regulating each of the nine biophysical Earth system processes and to connect substances, reactions, and chemistry concepts to sustainability science. The tool visualizes the dynamic interconnections among the Earth system processes and their control variables, enabling users to see changes of the Earth system over time (Fig. 4).[14]

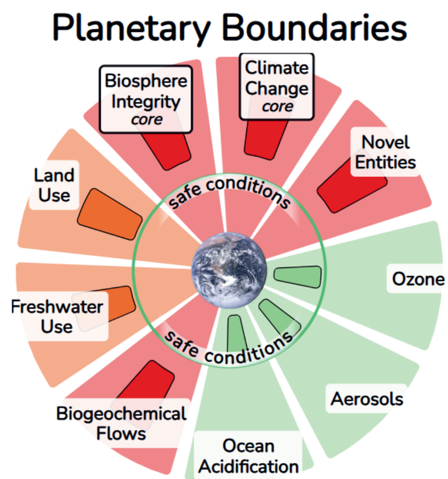

Fig. 4. Screen capture of the KCVS interactive *Planetary Boundaries Learning Tool*.

In conjunction with the same IUPAC project team, KCVS also created the *Sustainability and Systems Thinking in Chemistry Education* (*https://SaSTICE.com*) website,[15] which provides a starting point for educators wishing to use systems thinking approaches to connect chemistry teaching and learning to sustainability.

5. Visualizing IUPAC's Guiding Principles of Responsible Chemistry

Could your students articulate the key elements of what it means to practice chemistry responsibly? In July 2025, at the opening of the World Chemistry Congress in Kuala Lumpur, Malaysia, IUPAC launched its eight Guiding Principles of Responsible Chemistry (Fig. 5), a framework to define what it means to practice chemistry responsibly to address the most urgent needs of our planet and all its inhabitants.[16] The framework serves as a call to action for all those who practice chemistry and benefit from chemistry's applications to their lives, with a particular focus on scientists, educators, industry leaders, policymakers and the next generation of chemists. Each principle is elaborated with a set of compelling examples, a 'guiding future action' section, discussion questions, and references to explore the principle further. The IUPAC project group[17] encourages educators to integrate these principles into chemistry education at all levels.

Fig. 5. IUPAC's Guiding Principles of Responsible Chemistry.

KCVS collaborated with an IUPAC project team throughout the two years of the project to bring undergraduate student perspectives to the articulation of the eight guiding principles, and to design the IUPAC website[18] and icons that visualize the tagline descriptors of each Guiding Principle, as well as a downloadable infographic.

Collectively, these and many other open access interactive visualizations at kcvs.ca provide learning tools for the chemistry community to see and understand processes in chemistry and to explore how chemistry can contribute to solutions to complex global challenges.

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