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Perspective: The History and Future of Technology Paradigms

By Chad Dorsey

Three decades ago, the Concord Consortium began amid a wave of true technological innovation. As the public was still coming to grips with the very concept of a computer, the Web launched another new era—networked computing—that would change education and society forever. Over the ensuing thirty years, technologies have repeatedly converged, reshaping teaching, learning, and daily life. In their book *The Infinite Retina*, Irene Cronin and Robert Scoble frame the path to our current computing age as a progression of paradigms. This view provides a useful lens for parsing technology's past, and for identifying the trends that will define its future.

Progressing in paradigms. Personal computing formed the first and most fundamental paradigm. An age of enthusiastic garage hacking birthed the Apple I and II and their humbly accessible design. It also vaulted spreadsheets from concept sketch to business-world revolution and saw Dell's scaling innovations occupy home and office desktops around the world, seemingly overnight.

As these computers began to connect, Robert Tinker sensed a shift afoot. "The advent of community networking could revolutionize education," he wrote in the Concord Consortium's initial charter. "We imagine that kids anywhere could get on the network and explore interactive learning environments throughout the world that would convey important math, science, and technology concepts." These words would prove visionary.

Synergy in combination. Examining the rise of technology paradigms also allows us to see the synergies that span across them. The now-ubiquitous paradigm of mobile computing, arising hot on the heels of the personal computing era, provides a useful example. As mobile devices grew to occupy all corners of our lives and embraced the power of networking, they also opened opportunities for generating data from the world around us. From GPS data to personal health data and more, the data deluge that emerged from this synergy marked another important paradigm shift.

Similarly, the scaled growth of personal computing, combined with exponential advances in computing power, allowed computational modeling to transform both science and society. Synergies themselves can also combine to multiplicative effect: the expansive growth of computational models has generated a wholly new, massive source of data.

Interfaces as a throughline. One of the most important common threads across paradigms is subtle, but pervasive: each monumental advance has been possible only because of consistent advances in interface design. The earliest room-sized computers held huge potential, but it took the direct personal interaction from keyboards and peripherals to enable rich experimentation. Personal computers' inventive hacking days harbored tremendous innovation, but scaled only once graphical interfaces and direct mouse interactions opened the door for their intuitive use. Similarly, the true potential of mobile devices remained unrealized until the iPhone touchscreen provided a blank slate for interaction design.

This progression is a story of unrelenting evolution toward increasingly seamless, naturalistic interaction. Keyboards changed our punch cards into words. GUI folders and trash cans mirrored real-world objects. The mouse helped us recognize our ability to point to a location on the screen, then the iPhone let us point and drag directly. Interfaces have always moved toward approximating our physical world. Interactions leverage our real-world actions in ever-increasing measure.

Two technologies, one breathtaking new era. Today, two major technologies are poised to burst onto the societal scene, revolutionizing work, home, and education yet again. As we face this largely uncharted new world, past patterns offer useful insight. Looking carefully, we can see that each innovation arises from synergies among preceding paradigms, and that the consistent evolution of interface and interaction patterns fuels each revolution.

The first innovation, of course, is artificial intelligence. While AI itself is not new—most of today's stunning advancements have

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Transformations in teaching and learning have accompanied each technology paradigm.

incubated in one form or another since the 1960s—important synergies and interface advances have converged to bring about a clear phase transition. Early AI prototypes showed glimmers of possibility—from protein folding solutions to the stunning victory of a computer in the game of Go—but a new synergy among advanced computational models, mountains of available data, and massive advances in computing power has ushered in the true tipping point. And, as always, interface design proved pivotal in bringing AI onto the societal radar screen, as chatbots married the power of large language models with the familiar rhythms of human conversation. By moving closer to naturalistic interaction, AI became relatable, its power and ramifications recognizable across all manner of industry.

The second transformative technology of the coming era has yet to be fully realized, but arguably stands to bring even greater changes to our daily lives. Spatial computing, defined by Cronin and Scoble simply as "computing you move through," has been visible via incremental improvements in VR and AR for decades. However, Apple's recently introduced Vision Pro headset may offer the first real glimpse of spatial computing's potential for transformation.

Once again, paradigms converge. In spatial computing, networking and ubiquitous mobile technologies blend to form something wholly new. Foursquare and Pokémon GO demonstrated how mobile computing and location-aware networking might combine. Augmented reality apps and early VR headsets brought immersive environments to our living rooms. But spatial computing's true significance transcends these basic examples. With mobile computing, we expect to have computing power continuously *with us*. With spatial computing, we will expect computing power continuously *around us.*

The ability to "pin" screens anywhere in our world, from the office to the oven or along our morning walk, will fundamentally transform the way we view computing's role in our lives. Just as the Apple II evolved to the iPhone, now-clunky "ski goggles" will progress to seamless devices in invisible forms such as contact lenses, or to technologies we have yet to imagine. Spatial computing interface advances will be central to this transition. Ultimately, technology will layer onto our world, blending transparently into all aspects of life and leveraging our natural abilities to touch and grab real objects into intuitive direct manipulation of virtual objects. Computing will become more tangible, accessible, and powerful than ever before.

Implications for learning. Transformations in teaching and learning have accompanied each technology paradigm. As Bob Tinker forecast, networked computing allowed for advances in online learning and professional development and opened the door to collaborative data-related projects connecting students around the world. Synergy between mobile devices and computing power launched an entire probeware industry. Computational models paved the way for students to experiment with and understand otherwise inaccessible phenomena. The data revolution has shaped and highlighted the importance of creating powerful data exploration tools and learning experiences. From our very beginning, the Concord Consortium has been a pioneer in each of these paradigms. (Read more about Concord Consortium's three decades of innovation on pages 8-9.)

The coming era harbors an equally broad range of possibilities. With AI, learners may combine and evaluate unimagined molecular structures. Or they may explore physics and engineering concepts within free-range virtual worlds they instantly craft from photographs of their classroom, lab, or local neighborhood. With spatial computing, learners may move through data, visualize the foundational mathematics underneath a model or simulation, or create a new world with physical laws fully different from our own. At the Concord Consortium we are excited to explore these possibilities, and many more.

New Data Types and New Data Interfaces

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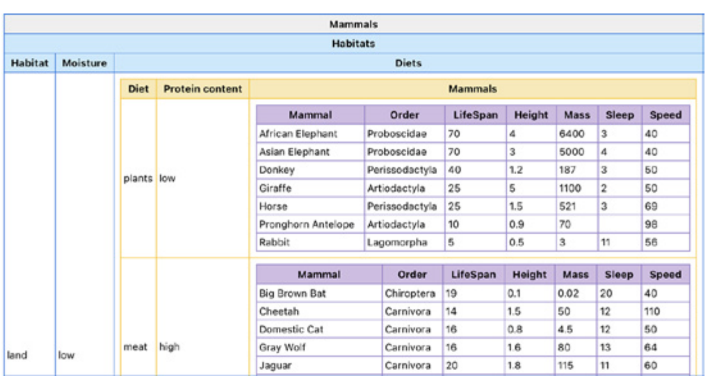
By Chad Dorsey

Working with data is a critical 21st century skill. Unfortunately, far too many students and teachers still examine data in spreadsheets using unwieldy or limited visualization tools. In the meantime, data has evolved. Today's datasets can be large and include data with complex structures and interrelationships, or the data may vary in both space and time. Ongoing research by the Concord Consortium and our colleagues is paving the way for novel interfaces and approaches that make such data explorable in new ways.

Multidimensional data: Thinking outside the "table box." Understanding the structure of an unfamiliar dataset can be challenging. While data are typically formatted in a two-dimensional "flat" display with rows of data for each item and columns representing data values or attributes about the items, this ubiquitous display is not as simple cognitively as it may seem at first.

Even relatively modest datasets can be organized or grouped by more than two attributes. Imagine a CDC dataset on vaccinations with five attributes presented by county. Depending on the question of interest or the user's perspective and preference, this dataset could be reorganized by state or categorized by ranges of the social vulnerability index. Such "nested" data structures transcend the confines of two-dimensional data tables, and working through potential restructurings places high demands on both the cognitive resources of learners and the flexibility of existing interfaces. Although students possess an intuitive understanding of hierarchical or nested structures, current technologies do not provide them the ability to represent these structures in useful and flexible ways.

In our Supporting Reasoning with Multidimensional Datasets project, we're working to identify how students represent, interact with, and make sense of multidimensional data, and to investigate how novel representations and interfaces can support them in sense-making and reasoning. We aim to help learners better understand dataset structure and ultimately promote the development of students' robust, flexible mental models of data. The exploratory interfaces we are designing within CODAP (Figure 1) show promise for helping students make sense of multidimensional data.



Mammals
Habitats

Habitat	Moisture	Diet	Protein content	Mammal	Order	LifeSpan	Height	Mass	Sleep	Speed
land	low	plants	low	African Elephant	Proboscidae	70	4	6400	3	40
				Asian Elephant	Proboscidae	70	3	5000	4	40
				Donkey	Perissodactyla	40	1.2	187	3	50
				Giraffe	Artiodactyla	25	5	1100	2	50
				Horse	Perissodactyla	25	1.5	521	3	69
				Pronghorn Antelope	Artiodactyla	10	0.9	70		98
				Rabbit	Lagomorpha	5	0.5	3	11	56
		meat	high	Big Brown Bat	Chiroptera	19	0.1	0.02	20	40
				Cheetah	Carnivora	14	1.5	50	12	110
				Domestic Cat	Carnivora	16	0.8	4.5	12	50
				Gray Wolf	Carnivora	16	1.6	80	13	64
				Jaguar	Carnivora	20	1.8	115	11	60

Figure 1. A new way to represent hierarchical data in CODAP using colors and a "box within a box" structure.

Spatiotemporal data: Exploring a new frontier. From climate concerns to public health needs to global issues across political or economic spheres, society's biggest dilemmas and our greatest opportunities involve interpretation of spatiotemporal data, data that vary across both space and time. However, such data pose myriad cognitive and technical challenges.

While techniques for analyzing either spatial or temporal data alone are established and robust, the overlap between attributes of space and time confounds even technical researchers in domains that depend upon these data—the first paper on big spatiotemporal data appeared in scholarly journals just over a decade ago. With that backdrop, we are pioneering work to understand how to aid learners in understanding and effectively exploring spatiotemporal data.

Through our Data in Space and Time project, we're conducting foundational research and development into how learners take in spatiotemporal data, and developing novel interface designs for spatiotemporal data exploration. We've begun by examining the different types of spatiotemporal data and conducting early research to understand how learners approach data of different types (Table 1).

Spatiotemporal data type	Data source/structure	Real-world applications
Event data	Measurements reporting point locations with associated timestamps	Crime, epidemiology, traffic accidents, social network activity
Trajectory data	Data from paths traced by bodies moving in space and time	Urban traffic, human mobility studies, animal habitats/ranges
Point reference data	Moving-reference-point measurements of a continuous spatiotemporal field	Weather balloon traces, sea surface measurements
Raster data	Fixed-location-and-timepoint measures of a continuous or discrete field	Climate, neuroscience, and transportation studies

Table 1. Types of Spatiotemporal data, data source, and sample real-world applications.

There are many different types of spatiotemporal data. This complication adds new challenges to designing appropriate interfaces. As shown in Table 1, data from individual events is fundamentally different from data representing a variable changing continuously across a map or data showing trajectories of multiple objects over time. Each data type corresponds to different real-world problems, and each holds its own questions for cognitive interpretation, interaction, and exploration.

Some of the most interesting questions, however, lie in what's not yet understood because it can't currently be explored. Imagine, for example, attempting to answer the question of when and where similar weeklong dips in surface water temperature have occurred across locations in the Gulf of Maine over twenty years. Or envision trying to explore which of a series of fifteen socioeconomic and environmental factors contribute most prominently to heat index-related medical admissions across a city over a decade. Answering such questions forms the core of dozens of present and future careers, yet current interfaces barely support their exploration. We aim to combine our research with related research on user interface design to develop novel technologies for data exploration. We also want to study how new visualizations can aid learners in approaching and identifying patterns in spatiotemporal data.

For example, consider data generated from discrete events. In such datasets, time adds a third dimension to the data that locate an event's position on an x-y coordinate plane. Researchers have experimented with representing time as a third dimension in the z-axis via prototype interfaces such as the space-time cube (Figure 2). Events occurring at specific map locations hold additional information about the time associated with the event. Tilting and rotating the space-time cube reveals this time coordinate and makes it possible to explore the data from multiple angles.

By pairing such an interface with CODAP's built-in ability to highlight selected subsets of a dataset across multiple representations, we want to understand how to help learners uncover new patterns in event data. For example, students might highlight the most extreme heat events in a city's history and observe where and when the highlighted data cluster together or see that certain locations exhibit more clustering in space and time than others. Or they might be able to move a 2D map layer up and down along the cube's z-axis to easily identify the geographical locations where time-event clusters occur.

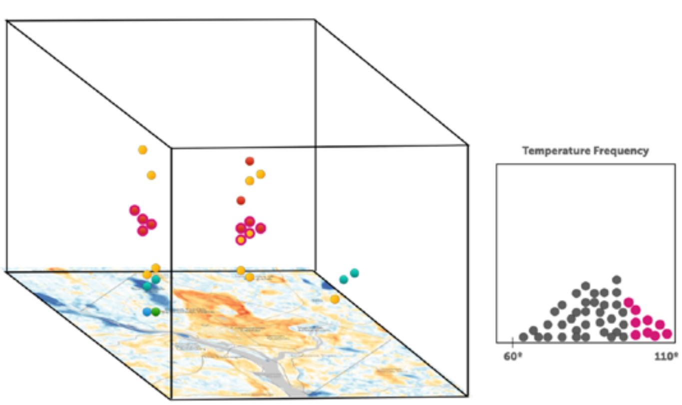


Figure 2. Students could use a space-time cube with dynamic linking to identify heat event clusters across a city such as Washington, D.C.

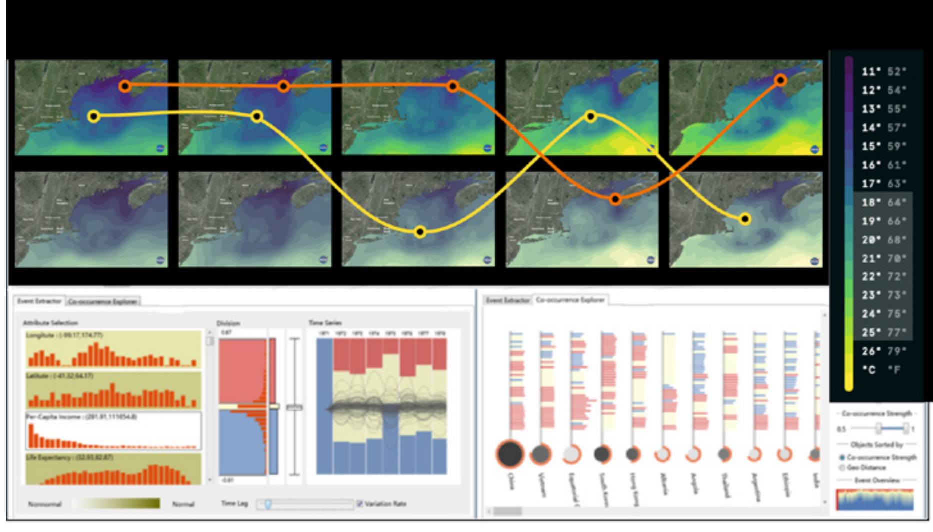


Figure 3. Students might use an event-tracking interface, such as the above modeled on the work of Li et al. (2018), to track marine warming events over space and time.

For other data types, such as raster data, or combinations of data types, we're researching new interfaces that will allow learners to explore multiple points on a map simultaneously. As Figure 3 shows, such interfaces will ultimately help learners identify correlations between dispersed patterns occurring at different locations or trace phenomena as they evolve across both space and time. Additional interfaces, supercharged by AI's capabilities, will allow for exploration currently only in the realm of imagination. We envision a "shape search" feature that allows learners to ask, "When and where has a similar shape occurred?" With such a feature (Figure 4a), learners might search for surprising temperature drops, data spikes, or U-shaped data trends across decades of historical data as easily as we search for text terms in a PDF file today.

AI technology also will allow us to collapse data from highly multivariable datasets intelligently into "super-hotspot" maps that show not only regions and clusters of geographical interest, but depict them clustered in correlation with each other. With such a tool (Figure 4b), learners could choose a handful of attributes of interest from dozens of columns in a public dataset spanning economic, social, and weather factors, and immediately see the geographic confluence of complex socioeconomic factors, temperature, and public health factors when added to a map.

Sonifying data: Adding accessibility for all. One of the most significant needs in data science education involves accessibility of data for learners with differing abilities. Blind and low-vision learners currently have practically no tools designed to support them in understanding and exploring data. Further, 75% of blind and low-vision learners are more than one grade behind their sighted counterparts in math and 20% are over five grade levels behind their peers.

To reach underserved learners and offer new ways of learning for all, we are exploring the potential of data sonification, adding audio information to data. With partners at Tumblehome Learning, we have developed interfaces for data sonification within

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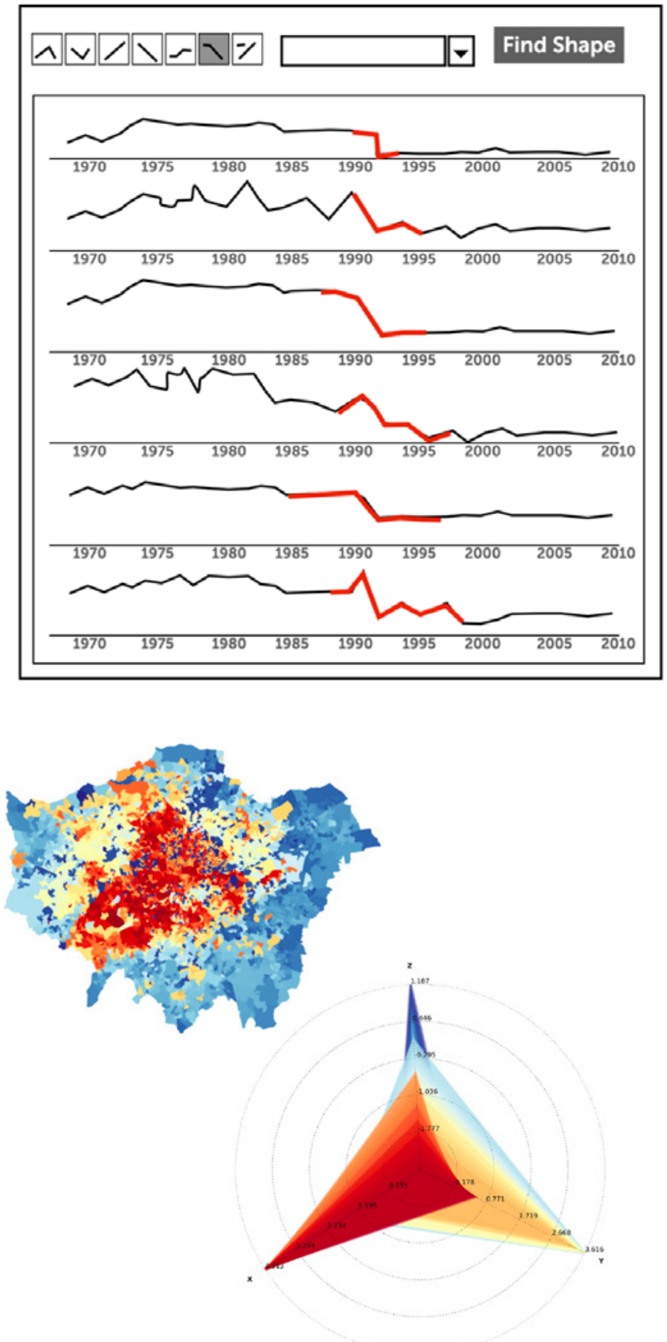

(a)

(b)

Figure 4. Students may use new interface paradigms to (a) search across a dataset for matching graph shapes, modeled on Gregory and Shneiderman (2012) or (b) combine multiple spatial and temporal parameters using methods inspired by Moosavi (2017) to surface "hotspots" that identify the most important correlations among them.

Gregory, M., & Shneiderman, B. (2012). Shape identification in temporal data sets. In J. Dill, R. Earnshaw, D. Kasik, J. Vince, & P. C. Wong (Eds.), *Expanding the Frontiers of Visual Analytics and Visualization* (pp. 305–321). Springer.

Li, J., Chen, S., Zhang, K., Andrienko, G., & Andrienko, N. (2018). Cope: Interactive exploration of co- occurrence patterns in spatial time series. *IEEE Transactions on Visualization and Computer Graphics*, 25(8), 2554–2567.

Moosavi, V. (2017). Contextual mapping: Visualization of high-dimensional spatial patterns in a single geo-map. *Computers, Environment and Urban Systems, 61*, 1–12.

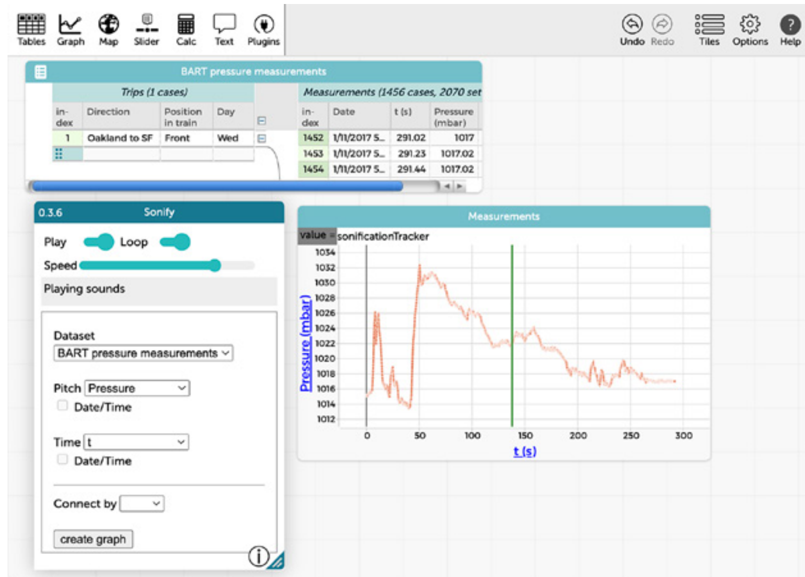

Figure 5. Students use CODAP's Sonify plugin to hear the changes in pressure over time experienced as a subway train enters and exits the tunnel connecting Oakland and San Francisco.

CODAP. We are now researching the extent to which linking visual representations with sonification can help students learn the basics of time-series graphs in more engaging and effective ways.

As shown in Figure 5, the sonification interface allows learners to select one or more variables within a dataset to explore via sound. By tying one attribute to the pitch of a sonified representation and another to the timed aspect, they can hear a scatterplot as a rising or falling set of multiple pitches and listen for the connection across variables. By selecting a single attribute for both, students can hear the shape of a bell curve or bimodal frequency distribution highlighted as regular variations in sonified output.

Perhaps the most interesting aspect of sonification lies in its capacity to extend our ability to explore data overall. Universal design solutions that serve one population often can serve many others. Discriminating pitch and time intervals using our innate auditory capacity can enable users to uncover surprising patterns or outliers that traditional data visualizations would otherwise obscure.

Our work is forging new ground and opening up completely new areas of research and development for new tools and new affordances. We will be sharing our results and publishing our tools as open-source software in order to inspire others. Today's youth need access to tools for learning and working with data that correspond to the challenges and opportunities they will face. By developing research-based solutions to these fascinating learning challenges, we're guaranteeing that the solutions available to them are up to the task and based on the best evidence available.

LINKS

Supporting Reasoning with Multidimensional Datasets—concord.org/multidata

Data in Space and Time—concord.org/dst

CODAP—codap.concord.org

Isles of Ilkmaar:

A Multiplayer Game for Teaching Data Science

By Lisa Hardy

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In the Isles of Ilkmaar, a fictional multiplayer game featuring an archipelago of diverse and magical biomes, middle school students are citizens of the islands who befriend and care for the local creatures. So what happens when their harmonious coexistence is jeopardized by a food shortage, or a novel illness that threatens the island ecosystem? Can game players work together using game data to restore ecological balance?

Data science is increasingly vital across fields, making middle school a critical time to cultivate data literacy. Our new National Science Foundation-funded research project is developing an innovative multiplayer game that immerses students in a vibrant world where their choices generate rich, analyzable data. We hope to illuminate promising pathways for engaging all students in the power of data science.

Designing a solution

Research has shown the importance of using data that connects to students' lives and interests to foster active engagement. Games can situate data practices within narratively rich worlds where data becomes a tool for achieving personally meaningful goals. In the Isles of Ilkmaar, students' actions in the game—from foraging for resources to interacting with the local creatures—all generate personalized data logs. This grounds data science in their unique gameplay experiences and goals.

What does data-rich gameplay look like? In the Isles of Ilkmaar, students navigate a rich ecosystem where their actions shape the world around them. As they play, the game generates a wealth of data, which becomes the fuel for both individual and collaborative investigations.

For instance, when some students want to bake the perfect cupcake to befriend a shy mushroom creature, they might analyze their own foraging records to find the highest quality ingredients. Noticing patterns in where and when certain resources appear, the students form hypotheses and adjust their foraging strategy (Figure 1). Or they might tap into the game's broader data pool, comparing their ingredients and outcomes to those of their classmates. The game's embedded data tools allow for easy querying and visualization, while a seamless integration with CODAP supports deeper explorations (Figure 2).

Figure 1. A player stands on Light Island, inspecting their Foraging Log to find the best ingredients.

Figure 2. A CODAP window with multiple visualizations of game data related to the island resources.

As the game narrative unfolds, students encounter more complex data challenges. A mysterious illness begins affecting the creature population, spurring students to role play as a medical team. They collect data on symptoms, administer treatments, and track recovery rates. To identify the underlying cause, students must think critically about how to merge and analyze data across multiple contexts, from the health clinic to the creatures' daily activities and diets.

These examples illustrate the kinds of authentic and purposeful data investigations the Isles of Ilkmaar aims to enable. Throughout their investigations, students engage naturally in the practices and thinking habits of data scientists. They learn to seek out sources of data, explore data to find patterns, and create visualizations to communicate their insights. By grounding data in an immersive, narrative-driven context with compelling goals, the game seeks to cultivate students' data literacy and spark their interest in data science.

What's next?

Our next stage of project research will focus on helping teachers leverage game-based learning to teach data science, while connecting it to disciplinary content and learning goals. If you are interested in exploring game-based data science learning with your students, sign up to be notified when the game is released (http://short.concord.org/lwo).

LINKS

Isles of Ilkmaar—concord.org/Ilkmaar

Three Decades of Educational **Innovations**

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Lee McDavid was the director of communications from 1997 to 2001.

By Cynthia McIntyre and Lee McDavid

When the Concord Consortium was founded in 1994, Google and YouTube didn't exist and Amazon was in its infancy.* Today, there are billions of searchable web pages and YouTube videos. Amazon customers currently place over 12 million orders per day. These staggering numbers highlight not only the growth of the Web but also the data deluge of the past three decades. Today, AI is crunching vast amounts of data, creating pathways to new solutions for seemingly intractable problems, and offering new opportunities for education. Thirty years has seen extraordinary advances in educational technology from online courses to web applications and the use of AI to support students. We are proud to be part of that history.

The Concord Consortium began with a handful of enthusiastic employees working out of an old house on Thoreau Street in Concord, Massachusetts, under a sign that announced our work as "an educational technology lab." We were led by the brilliant physicist Robert Tinker and the idea, revolutionary at the time, that technology could make a difference in education. Bob believed wholeheartedly in the power of curiosity to bring out the inner scientist in everyone. Our first grant from the National Science Foundation, called "Hands-On Physics," introduced themes that have been consistent throughlines over the three decades since our inception: student inquiry inspired by innovative educational technology and equitable access to digital resources.

Using inexpensive materials—the Hands-On Physics team made frequent trips to Radio Shack to buy all manner of electronics equipment from wire cutters to soldering guns—the project empowered students to gather their own data as real scientists do. No longer was physics merely abstract words in a textbook. Students were able to make independent discoveries about physical laws, investigating concepts such as thermal radiation, phase change, and other previously perplexing subjects. The development of powerful but economical technology, including the first educational probeware, was a game changer for science classrooms, especially those in underfunded rural and urban schools. Using probes connected directly to a live graph display of the data they produced, students explored their own ideas as experimental data collection became quick, easy, and accessible.

With innovation and access top of mind, the Concord Consortium anticipated online education's ability to cross geographic and economic boundaries as it developed the first virtual high school cooperative. "Brick and mortar" schools across the country could suddenly offer a wide range of high-quality courses previously unavailable locally: Advanced Placement, biochemistry, music, geometry, and much more. The Virtual High School project eventually spun off as an independent school (now VHS Learning) that offers over 260 different courses to public and private institutions, as well as homeschoolers. Paramount to the viability of this innovation was the development of interactive online courses, far more effective than simply video talking heads. To spur course development, the Concord Consortium developed a much-needed e-learning model, which would serve as a roadmap for anyone who wanted to develop online courses for students or teachers. These first "netcourses" and the inquiry-based model for online teacher professional development they introduced increased access to training and professional practices worldwide.

Making the invisible visible and explorable

Continuing our mission to engage students in science beyond the traditional lab, we developed the groundbreaking Molecular Workbench in 1999. Using sophisticated computational methods based on first principles (e.g., solving Newton's equation of motion for interacting particles), the Molecular Workbench simulates atomic-scale phenomena and permits students to interact with them.

Students from grade five through college could now experiment with atomic-scale systems to learn through exploring accurate simulations. The Molecular Workbench has since been used for topics in physics, chemistry, biology, and engineering, including gas laws, fluid mechanics, states of matter, chemical reactions, the genetic code, protein synthesis, electron-matter interactions, and quantum phenomena. But the real superpower of these simulations lies in their interactivity: students can manipulate variables as scientists do. With funding from Google.org in 2011, we made another innovative leap by reprogramming the models in HTML5 so they would run directly in modern web browsers.

By making Molecular Workbench simulations interactive, our goal was to help students develop a solid conceptual understanding that is difficult to achieve using traditional curriculum materials. Over the years, we have continued to develop numerous interactive computational models based on scientific laws. We have diversified our portfolio of educational simulations for studying genetics, evolution, earthquakes and volcanic eruptions, global warming, biological phenomena, and other science topics. These simulations empower students to do the previously unimaginable: manipulate the Earth's tectonic plates, modify genetic alleles, explore the relationship of various ecosystem components, and much more.

Hands-on learning is our byword for learning by doing. Technology not only offers the potential for engaging students in specific science topics but also forms a backdrop for learning about big picture concepts. These concepts, such as system modeling or computational thinking, play vital roles in our increasingly interconnected, technology-driven world. By moving learning past memorizing facts in a textbook or watching simplistic YouTube videos, technology can engage learners in generating and analyzing real data about topics they care about. In such cases, students take ownership of their learning, adopting new perspectives on the processes of science and how problems are solved.

In the last ten years, recognizing the importance of students' fluency with data, we have spearheaded efforts in data science education, spanning topics from social justice issues to climate data and more. These began with our development in 2012 of the Common Online Data Analysis Platform (CODAP), a web-based, intuitive tool allowing students as young as upper elementary age to analyze and understand complex datasets. We are also bringing together experts in data science to strategize about how to bring more data science into classrooms across grades and subject areas. Together with Data Science for Everyone, Valhalla, and the Gates Foundation, we recently founded the Launch Collective, a group of 30 practitioners, researchers, and developers with interest and expertise in K-12 data science education. This group is planning an inaugural Data Science Education K-12: Research to Practice conference in early 2025 to focus on connecting research and practice across K-12 data science education.

Looking to the future

We are also keeping our eye on AI. Students will need to know what it is and how it can be used. One new initiative is developing a year-long Artificial Intelligence in Math supplemental certificate program for secondary Algebra I or Integrated Math I classes. And, in a merging of our past with this new future, two public virtual schools will implement the program. In other projects, we are showing teachers how they can train and use AI to gather relevant information about their students' progress and better understand how to help them learn. (Read about our work in AI on page 16.)

Throughout all Concord Consortium projects, our aim is to make our work available to all by providing open-source software and openly licensed curriculum resources. Our STEM Resource Finder houses free activities and interactive computational models where teachers can easily create classes, assign activities, and track student progress. This is just another way the Concord Consortium continues to follow the values inspired by our founder Bob Tinker to expand educational opportunities to everyone, everywhere.

* Amazon was launched in July 1994, a month before the Concord Consortium's bylaws were signed. At the time, Amazon existed as a bookstore only, not the megastore it is now.

Note: The images for this article were created with ChatGPT.

LINKS

STEM Resource Finder—learn.concord.org

Capturing Moths
and Studying Data Science

By Sarah Haavind and Frieda Reichsman

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Frieda Reichsman
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Moths without mouths? Moths that can trick predators? Moths who favor a good IPA? Really? It's true—they like a tasty brew. These are some of the lesser-known facts about our ubiquitous nighttime visitors. Moths also are important pollinators as well as a key food source for birds, bats, and bears. Although moths are an essential element in ecosystems worldwide, little is known about moth ecology compared to other pollinators such as bees and butterflies. The MothEd project aims to fill this gap, offering students opportunities to do field science and engage in science practices in an area where many research questions have yet to be explored.

The National Science Foundation-funded MothEd project is co-designing an exciting field science curriculum with a team of three middle school and two elementary school teachers, entomologists from Michigan State University led by Peter White, researchers led by David Stroupe at the University of Utah, and software developers at the Concord Consortium under the direction of Frieda Reichsman.

The goal of the curriculum is to foster students' ability to develop and investigate their own research questions and their own systems for organizing and making sense of data they collect about moths in their local environment. MothEd uses our Collaborative Learning User Environment (CLUE) platform to frame and support students' research activities. CLUE includes a variety of features to help young scientists document their moth data, share their data and ideas, and engage with simple yet multi-featured tools for gathering and analyzing data to figure out what stories their moth data are telling them.

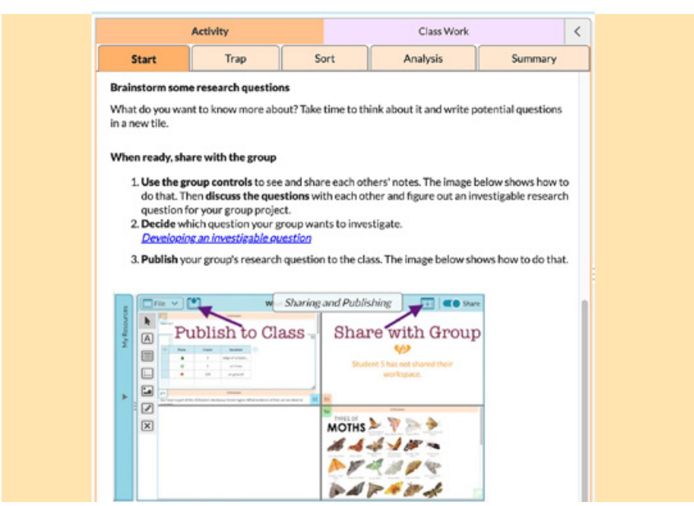


Figure 1. The MothEd activity in CLUE guides students through five stages of moth research, accessed by tabs. Students can share their work in CLUE in small groups or publish their work to the class for wider discussions.

After learning about moths in the "Start" tab of the online moth unit (Figure 1), small groups of students brainstorm investigable questions. Using CLUE, they document their questions and share them with their group mates or publish to the class for a full discussion of potential questions for field research.

Gathering data

Students build and set simple traps, guided by images and videos in the "Trap" tab. They bring what they capture into class to sort, pin, and photograph. (An upcoming article in *Science Scope** details the hands-on aspects of the curriculum unit in more detail.) Students record information about their captured moths using CLUE's data cards. Each card becomes a list where students enter relevant information about a specific moth they have caught, for example, the trap location under a tree, near flowers, or on a porch. The categories are chosen by the students, depending on what they are investigating. In addition, students are encouraged to describe several attributes that moth scientists also record, including the date of capture, image, and trap ID. Students can explore their data in various ways by grouping the cards into categories and transforming the data on the cards into graphs and tables. (For more information on data cards, see "Under the Hood: Data Card Deck" in the fall 2023 *@Concord*.)

Analyzing data

Imagine a group of students trying to figure out whether moths prefer visiting juniper trees, sagebrush, or rabbitbrush, all naturally occurring flora in their local high desert region. The students must first craft a research question together: *What types of native plants and trees do moths prefer?* The group's thinking is that if they know more about moth preferences, they may be able to take better care of the plants around them that benefit these native pollinators. Students set traps in three different areas, all at the same height and all on the same overnights, with the same forecast: little wind and no rain. They then document the moths from their trap on data cards in CLUE, and combine them into a larger stack of cards for the group (Figure 2).

As students review their data cards, they might notice additional variables they want to track, such as different wingspans. The additional data can be added to each data card later. When it comes time to sort the moth data into groups, by date, location, or color, etc., they may find that their data need to be "cleaned" to be more useful. For instance, different students might use different date formats or spell words differently, resulting in sorting the same data into separate groups. Once group mates combine their data cards by sharing their work with one another on the CLUE platform, sorting the cards into categories makes this cleaning easy. To unify the entries in a category, students simply drag cards from one category stack over to the stack that has the correct format or spelling, and the entry is automatically updated.

Sorting data cards so they are grouped into categories is a way of making data "hierarchical," similar to what data scientists do when exploring relationships among variables. Going from a single stack of cards to stacks that are sorted by moth color, for example, is a hierarchy by color. In the same way, a completely different hierarchy of cards would be made if moths were instead sorted by antenna type or body length. Younger students can be introduced to datasets with multiple variables using physical data cards, which can be sorted by hand into categories as students think about their data. This activity leads to the creation and sorting of virtual cards, thus scaffolding understanding of hierarchical data.

Interpreting data and revealing stories

With a single click in CLUE, students can create a graph from their data cards. Then they can easily change the graph axes to explore different questions they may have about how different variables relate to one another. At times, students expect certain patterns to emerge in their data. When alternative patterns emerge instead, students can easily explore them using data cards and graphs, forming new understandings of the world around them. The data representations are linked so that, for example, selecting and highlighting a value on a card highlights the corresponding point on a graph (Figure 3). Students can readily create multiple visualizations of their data, position them on the CLUE workspace, and take notes about their observations.

In the above scenario exploring moth preferences for different flora, sorting cards by location reveals that rabbitbrush is the clear winner (Figure 3a). Transforming the data into graph form allows quick, clear communication of this finding (Figure 3b). If other groups in the class also placed traps near juniper trees, sagebrush, or rabbitbrush for their investigations, their data cards could be added to these initial findings. Additionally, sorting data cards representing each moth into groups based on their categories eases the transition to graphing as students are more likely to realize that each point on the graph represents a single moth that they caught.

Understanding that moths may prefer rabbitbrush, students might then think about how they can preserve the flowering shrub that is often cleared from construction sites or consider planting it in their neighborhood or school grounds as a way to attract more pollinators. Working with local, meaningful data is a critical skill that can lead students to informed community service—and to finding interesting new facts about the world that is flying by.

* Keas, B., White, P. T. J., Brown, C. B., Stroupe, D., Best, S. G., & LeTarte, M. (in press). Conducting authentic moth research with students to encourage scientific inquiry. *Science Scope.*

Figure 2. Students have combined their individual card stacks in CLUE to create a larger stack with all the data from their small group. Now they are ready to sort the cards digitally, to look for patterns in the data.

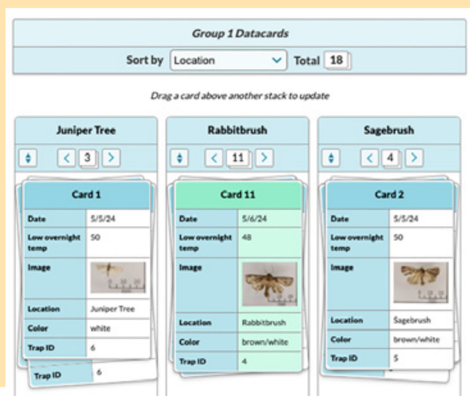


Figure 3a. Students have sorted their group data card stack by trap location.

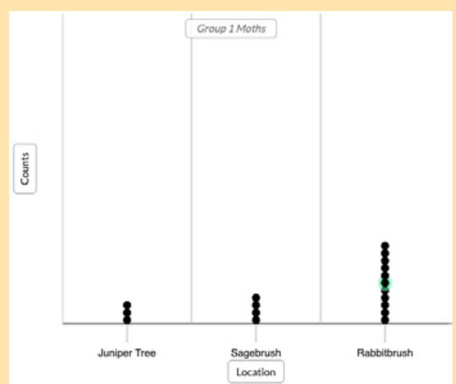


Figure 3b. To create a graph of their data, students click a button on their data card tile. Each point on the graph represents one card in the stack, and when students select a card, the corresponding point on the graph is highlighted, and vice versa.

LINKS

MothEd research–concord.org/mothed

MothEd curriculum materials at MSU–motheducation.org

Navigating the World of Units in M2Studio

By Kenia Wiedemann

Kenia Wiedemann (kwiedemann@concord.org) is a research assistant and project manager.

Dimensional analysis is an essential analytical tool connecting abstract mathematical concepts with real-world applications by ensuring the coherence of physical equations. A solid understanding of units and unit conversions is not just a mathematical exercise; it is central to mastering dimensional analysis principles and making sense of the real world. M2Studio supports students in mathematical modeling and the application of these principles.

Fluency in dimensional analysis lays the foundation for a scientific mindset. It allows students to apply abstract mathematical concepts to understand physical phenomena. This foundation cultivates a disciplined approach to problem-solving, critical thinking, and analytical skills. Such competencies are crucial for informed decision-making and innovation in our increasingly data-driven world.

M2Studio is a web-based learning environment designed to make dimensional analysis more accessible and comprehensible as students create, troubleshoot, and refine mathematical models, empowering them to tackle real-world problems. M2Studio is built into our Collaborative Learning User Environment (CLUE) software and provides students with a dynamic graphic interface for building and visualizing their reasoning through text, drawings, images, tables, graphs, and flowchart-style diagrams. With a wide set of tools, it appeals to a variety of learning styles. Further, the multiple representations within the various "tiles" (text, diagram, etc.) are seamlessly linked to each other, helping students make connections across these representations.

Variable cards and mathematical expressions

Students use the diagram tile to create visual representations of their models. In M2Studio, the variable cards are a particularly powerful representation that foregrounds dimensional analysis. When creating a variable card, students can customize it by giving it a name and adding the unit, value, and notes (Figure 1). A variable (e.g., *mass*) is thus represented as a card in the diagram tile, which can be moved around and used to perform operations and build a mathematical model to represent and solve a problem.

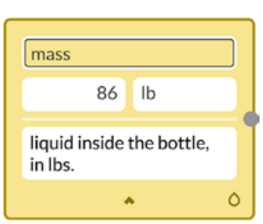


Figure 1. Students create a variable card and add its name, unit, value, and notes.

Students can link the variable cards to formulate and visualize complex expressions, such as the relationship between mass, volume, and density. They create an empty variable card to represent the result of a mathematical expression (e.g., *density* in the expression *density* = *mass/volume*) and connect multiple input cards to it by dragging a connection line from the input variables to the output variable. They then write the mathematical expression in the appropriate field of that card, using the connected input variables' names as well as numbers and operators. M2Studio automatically derives the units for the result, recognizing both singular and plural forms as equivalents (e.g., lb and lbs). It also allows students to mix different measurement systems as long as the units are equivalent. They can, for example, add miles to kilometers, and the result will be given in either system. These features reduce the friction of having to worry too much about spelling or navigating different unit systems, allowing students to focus on the modeling task.

M2Studio scaffolds student understanding

A unique feature of M2Studio is its handling of unit discrepancies. Students cannot simply choose the units resulting from a calculation to fit their expectations. Should students attempt calculations with incompatible units (e.g., adding pounds to cubic feet), the system highlights the error (Figure 2a). Students can then troubleshoot the units they used for the input variables and their mathematical expressions, delving into the "why" behind unexpected results. Was the error in the input units, the mathematical expression, or a misconception of the anticipated outcome unit? M2Studio instantly updates the model and final results to reflect any adjustments students make to the input variables and mathematical expressions. In addition, the output units can be converted to more appropriate ones (as long as they are compatible) by simply writing "*in [desired unit]*" (Figure 2b). This instant feedback mechanism fosters an iterative, discovery-led learning experience, invaluable for learning the principles of dimensional analysis.

An activity in M2Studio

The following activity showcases M2Studio's practical application by engaging students in an immersive, real-world problem-solving

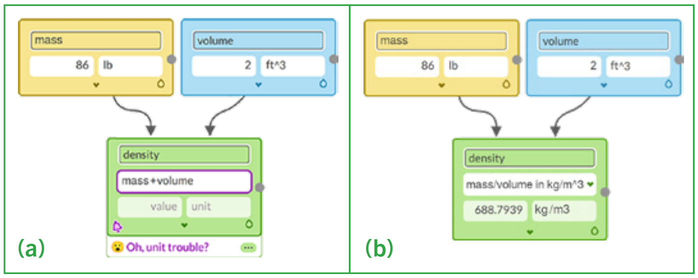


Figure 2. (a) When a student tries to perform an operation with two variables of incompatible units, M2Studio shows an error message.
(b) The student corrects the expression and the result is instantly calculated.

experience. Students consider a pressing environmental issue and take on the role of an environmental analyst with a mission to tackle food waste. This exercise is inspired by a recent law passed in New York,* which mandates that businesses and institutions producing over two tons of food waste weekly must donate edible items and compost the rest.

Students are challenged to select a college and, using actual data (e.g., the number of resident and non-resident students, number of school days, etc.), estimate if the institution would comply with a food waste law similar to the one passed in New York. Equipped with only two key pieces of information—the two tons weekly limit and an average food waste estimate per student per meal**—students use M2Studio to create a mathematical model to solve the problem. To calculate the total weekly food waste, students create variable cards to represent the total number of meals consumed by resident and non-resident students and apply the average waste per meal (Figure 3). To create an effective model, students are steered to use units properly, naturally applying dimensional analysis.

This exercise introduces the mathematical modeling process using variables with real-life implications, encouraging students to critically analyze their findings. For example, if their calculations show that

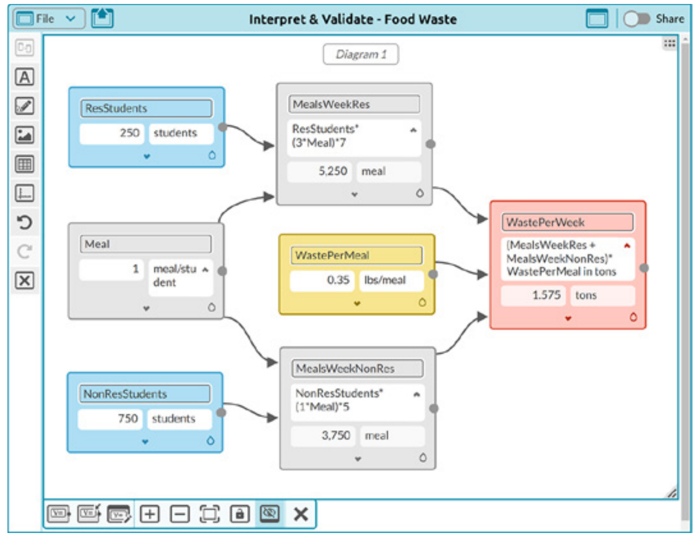


Figure 3. Students create input and output variables and manipulate them through connections and mathematical expressions to build their models. In this example, the weekly food waste (*WastePerWeek*) is calculated with the expression (*MealsWeekRes* + *MealsWeekNonRes*) x *WastePerMeal*, using input variables and other calculated values (*MealsWeekRes* and *MealsWeekNonRes*).

their college would exceed the two-ton threshold, students might test which factors play major roles in food waste, evaluate strategies for waste reduction (e.g., establishing a ceiling for the number of resident students), or analyze the effects of different solutions. In this activity, teachers can deepen students' engagement with the problem by considering a variety of outcomes and solutions or discussing environmental impacts.

Beyond numbers

M2Studio is designed to visually facilitate the troubleshooting of students' mathematical models. Giving students instant feedback on unit appropriateness and providing automatic unit conversions allows students to take a dimensional perspective before adding numerical data, building models with variable cards that initially focus on units, even without associated values (Figure 4). The iterative process of building, testing, and refining models cultivates an analytical mindset, empowering students to explore various scenarios, incorporate new elements, and adapt their models to address broader questions. By prioritizing the structural integrity of their models—ensuring that units align and that their results are plausible in terms of units and values—students sharpen their analytical skills and abstract thinking, learning to conceptualize complex systems without the immediate need for numbers. By supporting dimensional analysis, M2Studio highlights the profound lesson that mathematics transcends numbers, revealing its nature as a language of patterns, relationships, and logical reasoning.

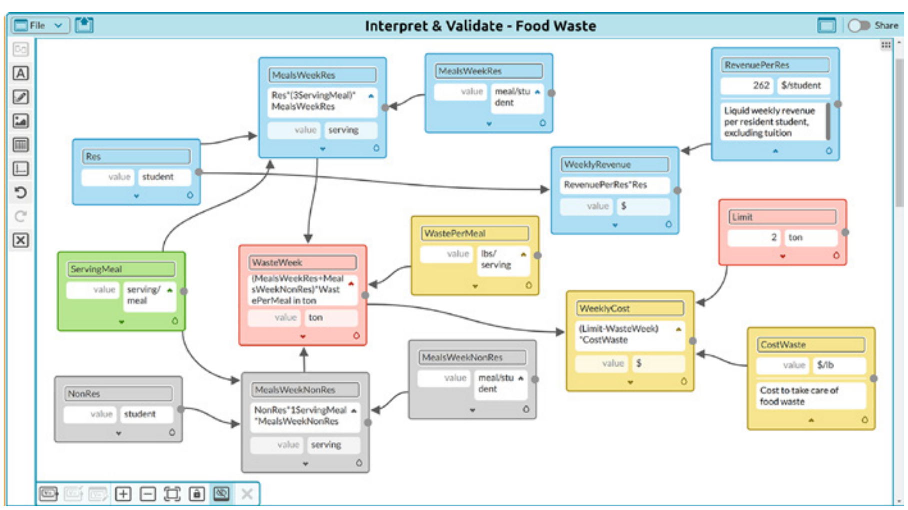


Figure 4. Students expand their models to add or modify variables, intermediate calculations, and dependencies. As they develop and refine their work, careful consideration of units and dimensional analysis takes precedence, fostering an understanding that mathematics extends beyond numbers.

* https://www.nysenate.gov/legislation/laws/ENV/A27T22

** The average waste per meal varies widely depending on the types of meals served and the waste reduction strategies in place. Students use a single value as a first estimate to simplify the exercise.

LINKS

M2Studio—concord.org/m2studio

Under the Hood: Sensemaking Rubrics for AI

Leslie Bondaryk
(lbondaryk@concord.org)
is the Chief Technology Officer.

By Leslie Bondaryk

A high school engineering teacher poses a problem: Design a solution for a home in a drought-plagued community to save and store water. Student groups start drawing and annotating their ideas. After some time, the teacher notices one group converging around a single concept: a rain barrel. Although she encourages the team to expand their thinking, they're stumped. The Mobile Design Studio (MODS) can help. It provides teachers and students with artfully chosen design heuristics that inspire creative problem-solving.

The challenge is how to get the right heuristic to the right student at the right moment. For teachers, helping students understand course content and identify their own progress within a sensemaking rubric is the challenge. MODS leverages machine learning to help teachers and students by using pattern recognition.

Machine learning, a specific branch of artificial intelligence, is a statistical system that finds patterns in human-readable work and identifies (or generates) those patterns in new work. Example documents that represent a pattern are first "tagged" by experts to identify important features, for example, the students' "converging design" idea in the rain barrel example above. Over time, as more examples are tagged, the system "learns" to recognize those patterns in untagged examples. And as long as the system has enough examples in each category to be able to distinguish them, there's no need to identify exact features that make an example fit one part of the rubric versus another. The most important part of the rubric application process is that it is consistently applied over lots and lots of example data.

Because sensemaking rubrics are unique to each discipline, we need subject matter experts on the new curriculum. A generic large language model such as ChatGPT would need this specialized training to work in this case. Participating MODS engineering and Earth science teachers who are familiar with the content score student work against the rubric. To streamline this task, we added a set of rubric tags (e.g., diverging designs, converging designs, etc.) to the comments section of our Collaborative Learning User Environment (CLUE) platform (Figure 1). Teachers select part of a student's design document (e.g., a particular sketch) or the whole document and add a tag to it (Figure 2).

The CLUE web-based platform supports a broad array of digital artifact generation (e.g., text, drawings, tables), and includes a robust action-logging system for tracking student use of the platform. This makes it an ideal system for AI data mining because all tagging, history, and content is digitized in a format the computer can search. This also allows us to get rubric training from the humans who know students best—their teachers.

Students' tagged work is sorted into the rubric categories, grouped alongside other student work. Since there are few wrong answers in a design engineering class, these groupings are not concerned with any notion of a "correct" response. Instead, they are designed to help students articulate the sensemaking stages within the class and to locate their own position within those stages. By introducing students to a rubric for contextualizing their work and helping them recognize those contexts in their own or their peers' work, we hope to encourage them to be more engaged and motivated learners. Over time, the automated system will be able to categorize future work and achieve the holy grail of AI for engineering design—recommending new design heuristics to students.

Figure 1. Code in the CLUE platform for tags associated with design heuristics (e.g., the *user*, denoting who the object is designed for; the *environment*, which conveys where it will be used; its *function*, etc.).

```
"config":{
    "showCommentTag": true,
    "commentTags": {
       "diverging": "Diverging Designs",
       "converging": "Converging Designs",
       "user": "Who's it for?",
       "environment": "Where's it used?",
       "form": "What's it look like?",
       "function": "What's it do?"
    },
    "tagPrompt": "Design Focus",
    ...
}
```

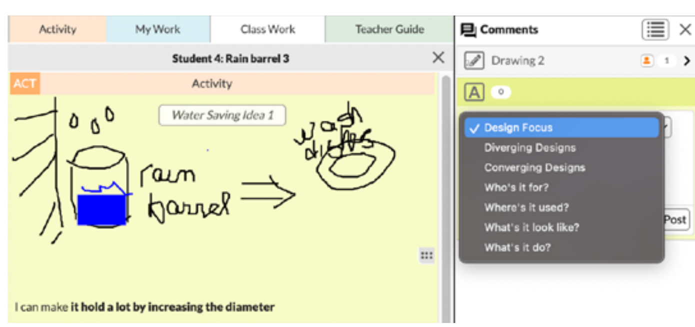


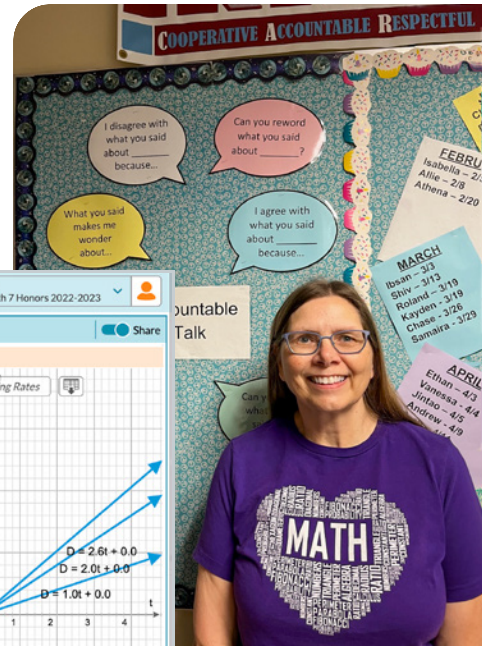
Figure 2. Teachers can select part of a student's design (e.g., a particular sketch) or the whole document and add a tag to it that describes the sensemaking stage.

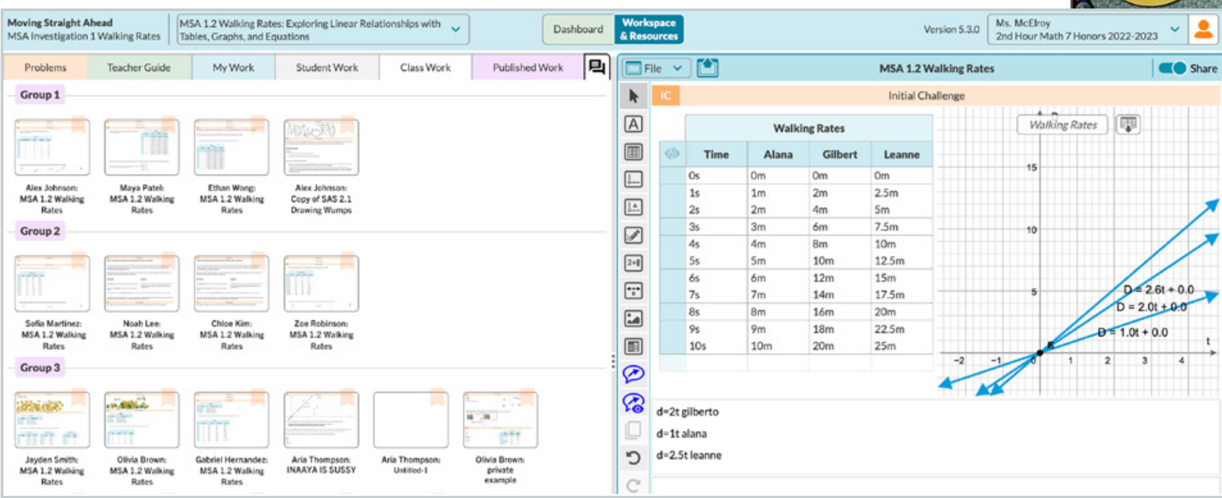
LINKS

Mobile Design Studio—concord.org/mods

Teacher Innovator Interview: Marian Murembya

Middle school mathematics teacher
Okemos, Michigan





Marian can view students' work in the CLUE platform.

Marian Murembya was the fifth child in her family. She laughs when she describes her parents as "worn out" by the time she came along, but she's glad for what that offered her childhood. "I was a free range kid who did a lot of exploring," she muses. Her parents also encouraged Marian and her siblings to ask questions, which she did in abundance. These qualities would become the touchstone of her educational philosophy.

But her path to the head of the classroom was not straightforward. While Marian took education courses during college—she figured they would be helpful for future parenting—she did not become a teacher immediately after graduation. Instead, she took a job as a deckhand on Lake Superior, then wrote for a local magazine, and worked in the printing business. After a decade of "doing all kinds of different things," she moved from the Upper Peninsula to Okemos, Michigan, and opened a children's bookstore, where "it was nice to see kids get excited about learning." Two years later, after the bookstore closed, she earned a teaching certificate, so she could help more children experience that same excitement.

During a pilot program at Michigan State University (MSU) for pre-service teachers, Marian was introduced to a series of math methods courses, which spoke to the way she had learned. The middle grades math project, a precursor to MSU's Connected Mathematics Project (CMP), emphasized questioning and collaborative problem solving.

Marian has been a middle school mathematics teacher in the Okemos district for over 30 years, teaching the CMP curriculum through all its versions. She is now a research participant in the Digital Inscriptions project, a collaboration between the Concord Consortium and Michigan State University, which has embedded CMP into our Collaborative Learning User Environment (CLUE) platform.

Despite the new online platform, Marian has stuck to some of her tried-and-true methods. She still groups her students in the same way whether they're working online or with paper and pencil, and she sets the same expectations for how they should talk to each other when solving math problems. Another constant is her consistent use of two questions she asks her students: *Why do you think that?* and *What do others think?*

According to Marian, the biggest change is how students are learning within CLUE. "They're more willing to try things because the digital tools allow them to do that." Marian goes on to say, "Technology is a good thing, but kids need to know what to do with it." For instance, while she doesn't require that her students plot points by hand (the technology can assist with that task), she is clear that they need to be able to see the patterns and relationships in the graphs they make. Students, she says, should "muck about in the math."

Marian is also excited by CLUE's ability to allow students to join their classmates in online groups from anywhere and for her to see their work in progress. During COVID, for example, students from home could join groups, and she recently had a student who was in India participate in group work from a distance.

Marian thinks deeply about how her students are thinking and "what things are going to trip them up." Her fondness for questions and problem solving led her to organize a Tuesday night "math circle" where students solve math problems for fun. Her approach is much like one of her favorite fictional characters, the inquisitive private investigator in the No. 1 Ladies' Detective Agency series. To Marian, math is just another delightful mystery to unravel.

The Concord Consortium
25 Love Lane, Concord, MA 01742

The Concord Consortium is spearheading a number of initiatives in the field of artificial intelligence. Leslie Bondaryk is the Chief Technology Officer and a fellow in EDSAFE AI Alliance's Women in AI Fellowship program. Jie Chao is director of a new AI in Math $4 million project funded through the Education Innovation and Research program at the U.S. Department of Education. We asked them to reflect on AI in education.

Q. Why is artificial intelligence important to education?

Chao: There are two main categories of work in AI in education. The first is looking at ways to use AI to help students learn and teachers teach. This is the important work Leslie is doing. I'm focused on the second main category, which is helping students learn about AI. The inequalities arising from current AI development are partially rooted in the unequal access to AI educational opportunities. I'd like to see that change.

Bondaryk: The very best teachers watch a student progress over weeks, months, or even years to help them reach the next level in their educational engagement. AI has the potential to support teachers in tracking students' development and making timely interventions. I'm excited about the work we're doing on the Mobile Design Studio project to make this happen. (See the "Under the Hood" article on page 14 for more details.)

Q. Why do you think AI belongs in K-12 education?

Chao: Teaching AI seems like a very narrow topic that belongs in computer science classes, but there's a wave of technology advancement that is going to affect all of society. Basic AI literacy is going to be a necessity. All students need to learn how AI works and how AI is developed, and then build on that knowledge to become AI developers or professionals able to use AI to solve real-world problems.

Bondaryk: I don't think there's a place where AI doesn't belong. Talking to ChatGPT is like having a good brainstorming partner, not because it's smart exactly, but because its knowledge of the universe is very broad. AI can help teachers recognize various patterns in student learning, or be a good "partner" for a student who wants to cultivate an idea. It's time-consuming and in some cases impossible for a human to preconceive every helpful response for a student. An AI system can look at what a student is doing and figure out the appropriate response based on the patterns that it identifies in their work or questions.

Q. What is the future of AI in education?

Chao: It's really hard to say what the future looks like at this point because there is an established infrastructure of how education is done right now. If we work with what exists, the application of AI to support teaching and learning has to feed into existing practices. If you look into the very far future, rethinking learning from the ground up and looking at how AI can play a role, the potential is enormous. I recommend reading *AI 2041: Ten Visions for Our Future* by Kai-Fu Lee and Chen Qiufan.

Bondaryk: When people say they want to be cautious about introducing AI into classrooms, I don't think we need to be worried about creating a replacement for good teachers. We need to be concerned about where the source material came from. Generative AI is only as good as the data that it's fed, and it's pretty easy to make it support your own biases. I hope that as a country and society we can agree that we need definitive information and unbiased systems. We know how to make them happen, we just have to take the time and money to create them, and to make them available to everyone.

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