Supplemental Material

CBE—Life Sciences Education

Gardner *et al*.

Definitions, Scope, & Underpinnings

Graphing is widely recognized as a foundational competency for learners of all ages as graphs play a unique and essential role in communicating information relevant to one's professional and daily lives. In the sciences, graphs are used as a core visualization tool to represent quantitative data to model, explain, and/or predict complex natural phenomena. Underpinned by diverse cognitive processes, the learned activities of graph construction, reading, interpretation, and reflection are inextricably linked.

[+ Definitions]

- **Authentic data** is quantitative or qualitative information collected from real-life phenomena that result from scientific observations or investigations.
- **Authentic research** occurs when inquiry is conducted in which the outcomes are not known to the people conducting the work nor the greater research community.
- **Data visualization** is the representation of data as organized into a visual format which can be generated within one's mind (internal 'mental' data visualization) or within the public space (external data visualization). External data visualizations include graphs, tables, infographics.
- **Graphs** are a model with at least two scales and values associated via a symmetric 'paired with' relationship.
- **Graph choice** occurs when a graphical representation (e.g., bar, line, scatter, histogram, box and whisker plot, and pie graphs) is selected often according to the data available (i.e. categorical or continuous) for graphing.
- **Graph comprehension** is an individual's ability to make sense of and use graphs created by others or by themself.
- **Graph construction** is the process of translating data into a type of graphical representation (change to planning, construction, reflection.
- **Graph evaluation/reflection** consists of the ability to (1) properly identify the advantages and disadvantages between different graphing modalities and (2) understanding whether or not the graph is conveying misleading information.
- **Graph interpretation** - The process of making inferences from information extracted from a graphical representation of data in the context of what is known about the biological system under study.
- **Graph knowledge** is an understanding of the appropriate usage of different graph types.
- **Graph literacy** is the ability to depict and obtain meaning from graphical representations that communicate information in the context of a discipline or one's daily life.
- **Graph reading** - The process of extracting information from a graphical representation of data. This is necessary for and distinct from graph interpretation.
- **Graphing** - A collective term inclusive of graph construction, graph evaluation, graph interpretation, and graph reading.

- **Messy data** are data that contain variation that arise from natural sources (i.e. biological variation), variation during its acquisition, and human error.

- **Models** are simplified representations of a natural or social phenomenon, which, depending on its purpose, emphasizes specific aspects of the system (e.g., components, processes, or system function).

- **Quantitative reasoning** is a habit of the mind in which quantitative elements are recognized, evaluated, constructed and communicated in one's public, professional, and personal life.

- **Scaffolding** is a process through which an instructor adds support for students in order to enhance learning and aid in the mastery of tasks. Often this involves the instructor modeling how to work through a new task or strategy, then the instructor works together with the class to perform the task, and finally students work cooperatively together to master the task.

- **Visuo-spatial reasoning** is a mental process involving the creation, transformation, manipulation, and interpretation of physical representations present in visual form and with components that are spatially related to and segregated from each other.

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[+ Scope]

- This guide focuses primarily on the teaching and learning of graphing, or the practice of reading, interpreting, creating, and evaluating graphs. While graphs are a type of model, the references included here relate specifically to how learners make sense of and use graphical data given the importance of these displays in science and "everyday" communication.

  For those interested in modeling in the classroom more broadly, we encourage readers to visit the corresponding LSE evidence-based teaching guide on this topic.

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[+ Underpinnings - The Cognitive Basis of Graph Competence]

- Students enter the undergraduate classroom having had regular, varying prior experiences with graphing in their daily lives and earlier instruction, influencing how they reason with and use graph data.
- Graph comprehension is a multiphase cognitive endeavor incorporating the alternating cycles of perceiving a data representation and integrating disparate knowledge into the representation.
  - These processes are influenced by the graph display characteristics and the interactions between one's top-down (i.e.perceptions based on prior knowledge and expectations) and bottom-up processing (i.e. perceptions based on real-time presented sensory information).
- Graph reading, interpretation, construction, and evaluation (or reflection) are interrelated practices that contribute to one's ability to make sense of and use graphical displays. These activities are underpinned by unique cognitive processes that can be taught and learned.

    - There are a range of instructional practices that can support the cognitive development of students' graph-based reasoning by situating graphing in the domain of practice, including:
        - Employing iterative graphing exercises with explicit feedback
        - Scaffolding activities and assessments with data of varying forms at different levels of cognitive complexity
        - Using contextually appropriate displays of graph data.
        - (See Design section - link)
- Graph construction and computer-aided data visualization are distinct cognitive processes that should be instructionally decoupled to benefit student graphing skills.
- Individuals with higher levels of expertise perceive graphs differently than more novice viewers due to variation in the ability to activate prior knowledge (graphing and domain-specific) relevant to the presented data.
    - Design features have a substantial impact on the graph reasoning of novices who often rely on superficial aspects rather than salient data relationships. It is important that instructors are purposeful in the selection and use of graphs to present information congruent to students' prior knowledge and identified learning objectives.

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[Article] **Friel, S. N., Curcio, F. R., & Bright, G. W. (2001). Making sense of graphs: Critical factors influencing comprehension and instructional implications. Journal for Research in Mathematics Education, 124-158.** This seminal article serves as one of the first efforts to bring together ideas from varying research perspectives (e.g., psychology, statistics, literacy, education, and information processing) to explore a framework of critical factors that influence graph comprehension, which the authors define as the "graph readers' ability to derive meaning from graphs created by others or by themselves". Here, graph comprehension is proposed to involve four kinds of behaviors, including: (1) translation – a change in the form of communication between tables and graphs, (2) interpretation – identification of relationships, (3) extrapolation and interpolation – noting trends perceived in the data and potential implications, and (4) questioning – question asking and question posing that allows the reader to explore the presented data. Additionally, several critical factors that influence graph comprehension including the purposes for using graphs, task characteristics, discipline characteristics, and reader characteristics are identified and explored. The authors outline three levels of graph comprehension that "show a progression of attention" from local to global features of a graph focusing on directly extracting data from a graph, (b) finding relationships in the data ("seeing between the data") to extrapolating or making inferences about relationships implicit in a graph ("seeing beyond the data"). In consideration of these factors, instructional recommendations are provided relating to behaviors that demonstrate one's ability to use graphs, a suggested progression of graphs for K-12 instruction, and the creation and adaptation of graph data to promote sense making.

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[Article] **Freedman E.G., Shah P. (2002) Toward a Model of Knowledge-Based Graph Comprehension. In: Hegarty M., Meyer B., Narayanan N.H. (eds) Diagrammatic Representation and Inference. Diagrams 2002. Lecture Notes in Computer Science, vol 2317. Springer, Berlin, Heidelberg.** In characterization of the factors that influence graph comprehension, the authors propose the construction-integration (CI) model that incorporates the effects of prior knowledge and display characteristics. Within this model, successful graph comprehension occurs in two phases, occurring in alternating cycles, including one's construction of a coherent representation of the presented information and then integration of disparate knowledge into the representation. The proposed model for graph comprehension accounts for the interactive influence of graphical display features, the viewer's graph reading skills (interpretation propositions), and domain knowledge. As it relates to visual display, the authors explain how display features can influence graph processing (e.g., visual chunking, data transformation). The authors further outline how several types of prior knowledge (domain knowledge, graphical literacy skills, and explanatory skills), activated early during processing, can influence the viewer's graph comprehension. The model highlights the potential interplay between one's knowledge about graph formats and expected relationships between variables leads to a top-down influence on graph interpretation. This is particularly relevant in scientific reasoning as experts, in contrast to novices, may offer explanations beyond the presented data by drawing on prior knowledge automatically activated in the construction phase. One important consideration for instruction here, is that novices may be unable to activate their prior knowledge automatically, and may then rely on superficial aspects of the data rather than the relevant relationship. Thus, instructors (as well as practitioners presenting graphs to the general public) need to be attentive to presenting graph information in a means that is congruent to the viewer's prior knowledge and task goal as non-optimal displays will lead to biased and inaccurate decision-making.

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[Article] Hegarty, M. (2011). The Cognitive Science of Visual-Spatial Displays: Implications for Design Topics in Cognitive Science 3 (2011) 446–474 DOI: 10.1111/j.1756-8765.2011.01150.x. This review article provides a cognitive science perspective on the design and use of visual-spatial displays. The author begins by identifying and discussing three broad types of visual displays based on the relation between the representation and its referent (i.e. what the symbol/representation refers to) and the complexity of the information being represented, including: iconic, relational, and hybrid displays. The article then outlines how visual-spatial displays enhance cognition by freeing up working memory, utilizing spatial organization, offloading cognitive processes onto perceptual ones, and offloading internal mental computations onto the external manipulation of complex interactive displays. The author next outlines the cognitive and perceptual processes involved in understanding visual-spatial displays. As described, display comprehension involves the complex interactions between top-down (perception driven by prior knowledge and expectations) and bottom-up processes (perception driven by sensory information as it comes in) mediated by the visual features of the display and the viewer's expectations of what is salient, display schema (a construction of a representation of a referent) that includes knowledge of display conventions, and domain knowledge or visual-spatial processes (e.g., mental rotation, comparison). Finally, the author discusses relevant findings (or principles) in cognitive science and related fields to inform the design of effective visual-spatial displays. Several of the summarized principles (e.g. those related to task specificity, perception of displays) are especially relevant to the use of graph displays in teaching as well as in training students best practices for presenting scientific data.

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[Article] **Lehrer, R., & Schauble, L. (2000). Developing model-based reasoning in mathematics and science. Journal of Applied Developmental Psychology, 21(1), 39-48.** The ability to understand and use models and modeling is widely seen as being central to an understanding of science. In this review, the developmental trajectory of students' model-based reasoning and key aspects of teaching and learning activities in science and mathematics that emphasizes systematic practice in the construction, evaluation, and revision of models is explored. Drawing on their work with elementary learners, the authors identify and discuss four forms of modeling as cognitive tools that they feel support student learning: physical, representational (e.g., graphs), syntactic, and hypothetico-deductive models. This is followed by a description of related modeling practices and how they relate to the development of learners' model-based reasoning. While the authors' insight stems from work with young children, the provided suggestions are also largely applicable to college science learners as model-based reasoning develops over years and is contextually situated. Of particular relevance to graph instruction, the authors make a case for the (a) iterative, cyclical nature of modeling in which students evaluate multiple models and receive explicit feedback to the appropriateness of their ideas; (b) situation of models in interesting and approachable problems; and (c) value of modeling in the domain of practice. The authors conclude by advocating for curricula that explicitly focus on models and modeling for the development of model-based reasoning over the "long journey" of one's learning.

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[Article] **Wang, Z. H., Wei, S., Ding, W., Chen, X., Wang, X., & Hu, K. (2012). Students' cognitive reasoning of graphs: Characteristics and progression. International Journal of Science Education, 34(13), 2015-2041.** This article makes use of a graph information framework to characterize the types of reasoning high school science students employ when reading and interpreting graphs. Building from a review of the literature on the components of graph comprehension, the authors created a framework comprised of three types of graph information: 1) Explicit information presented in graphical elements (e.g. plotted variables, data points, straightforward variable relationships), 2) Tacit information that requires prior scientific knowledge and mathematical tools to draw inferences beyond the presented data, and 3) Conclusive information visible from deep reasoning in deduction and graphs analysis. To examine the characteristics and differences of graphing skills among students at different grade levels, ~3000 high school students in China a validated assessment consisting of open-ended items to reveal their ability to read and analyze scientific graphs. The authors used their framework to analyze student responses and categorize student reasoning with graphs. The authors found that across the grade bands, student use of explicit information did not vary, whereas, a difference in the use of tacit and conclusive information requiring an understanding of scientific concepts was observed. In comparison to their younger classmates, students in Grade 11 were more likely to "look" past the surface features of the graph and draw on their more advanced scientific knowledge to make sense of the presented data. However, the type of graph did have an impact on student responses with the more experienced students using tacit and conclusive information for graphs that depicted complex scientific concepts or for which the relevant concepts are not explicitly plotted.

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[Article] Padilla, L. M., Creem-Regehr, S. H., Hegarty, M., & Stefanucci, J. K. (2018). Decision making with visualizations: a cognitive framework across disciplines. Cognitive research: principles and implications, 3(1), 1-25 This review outlines a generalizable cognitive model as to how people make decisions with visualizations to inform effective visualization design, including graphs. The integration of visualization cognition frameworks with a dual-process account of decision-making, including automatic, simple decisions (Type 1) and more complex, contemplative decisions (Type 2) are explored. The dual-process model outlines how individuals create a mental schema from a visualization and conceptual task using top-down (i.e. our thinking affects what we see) and bottom-up (i.e. Visualization affects our thinking) encoding mechanisms that includes working memory. Based on cross-domain findings, four common universal visualization principles relevant to graph design and instruction are suggested. First, early stages of decision-making are profoundly influenced by one's bottom-up attention. This suggests that a graph designer's effort should be placed on focusing the viewer's attention on critical task-relevant information to positively capitalize on Type 1 processing while limiting potential distractors that result in poor decision outcomes. Second, in relation to Type 1 processing, is the potential for visual-spatial biases (e.g., tendency to use the first data point to make decisions, belief that higher-quality images reflect "better" data, etc.) that can be both beneficial and detrimental in early decision-making. Third, involving Type 2 processing, is that if a mismatch occurs between the visualization and one of the decision-making processes, then a mental transformation will be required that can be error-prone and increase time on task. Thus, efforts should be taken to identify and reduce potential mismatches to reduce the number of transformations required in the decision-making process by examining the alignment (cognitive fit) of the visualization and task. Fourth, is that an individual's existing short- and long-term knowledge can interact with visualizations (bottom-down). The authors contend that there is an interplay between Type 1 and Type 2 processing in how viewers complete visualization tasks and they recommend practical recommendations for visualization designers and instructors.

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[Article] Shah, P., & Freedman, E.G. (2011). Bar and line graph comprehension: An interaction of top-down and bottom-up processes. Topics in Cognitive Science, 3(3), 560–578. This study builds from a model of display comprehension in which the features of the display interact with the prior knowledge and viewers' expectations which influences understanding of the display and inferences drawn. In particular, the authors aimed to examine how domain-specific knowledge of graph data and domain-general knowledge about data display affect one's graph interpretation skills. Fifty-five undergraduates were randomly assigned to a set of 14 bar or line graphs that represented comparable data of medium complexity (i.e. multivariate data with three variables represented) and varying familiarity to examine their graph interpretation skills. Each graph had an accompanying paragraph contextualizing the data, but omitted the outcome of the study from which the data came from. Participants were prompted to write a short summary of what they perceived to be the important take-aways from the presented graphs as well as their familiarity with the included data relationships. In follow-up, participants completed a short graphicacy assessment as a measure of competence of both basic graphing skills and the tasks in the study. Results indicate that participants focused on x-y axis trends when viewing line and bar graphs with unfamiliar variables. In comparison, when the variables were familiar, participants were more attentive to y-z axis relationships, with this pattern being significant for those with measured high graph interpretation competence. These findings provide the first test of a top-down/bottom-up model for graph interpretation and highlights the interaction of domain-general graphing features (e.g., graph type) and the role of domain-specific knowledge for this process. Such insight can help instructors consider how to develop differentiated scaffolding (by graph type and familiarity with the variables) to support student development of graph interpretation skills.

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[LSE] Quillin, K., & Thomas, S. (2015). Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. CBE—Life Sciences Education, 14(1), es2. While not specific to graphing, this essay provides a drawing-to-learn framework that defines drawing, provides examples of various types of drawing in biology, and explains the cognitive benefits of students drawing models to reason in the biology classroom. Instructionally several tools and best practices are suggested to foster an environment that supports drawing-to-learn interventions. The authors also outline a Blooming tool for drawing model that provides a scaffolded framework that applies Bloom's taxonomy to assessment exercises, including various examples and suggestions for instructors in how to work up cognitive levels. For graphing, a suggestion for the lowest-order cognitive level of knowledge, is to give students the independent and dependent variables and ask them to draw and label the axes on a graph. At the comprehension level, an example exercise is to have the student explain what a data point represents. At the application level, students draw a graph based on a given set of data. At the analysis level, the suggestion is to have students build on the application level and have them determine if the data support or reject a hypothesis. At the synthesis level, the suggestion is to design an experiment to answer a question and sketch a graph of the prediction. At the highest-order cognitive level, evaluation, it is suggested to have students evaluate a graph to determine whether it is constructed appropriately to the data provided. The drawing-to-learn framework and Blooming tool provide instructors a structure of best practices for the incorporation of drawing into the classroom in benefit to student learning.

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[Guide] Modeling This guide describes the efficacy of the practice of scientific modeling for the development of students' conceptual understanding and systems thinking skills. It also highlights a variety of common (non-graph) models, and practical approaches for instructors to incorporate models and modeling into the classroom, which could include graphing.

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[Resource] Tufte, E. R. (2001). The visual display of quantitative information (Vol. 2). Cheshire, CT: Graphics press. Widely held as the seminal text on how to understand and depict data, the book can help guide students and practitioners in the theory and practice of quantitative data visualizations. The book provides practical insight and examples (good and bad) to demonstrate how to effectively display data graphically. Highlighted topics include the design and selection of graphical displays, editing and improving graphics for aesthetics and analysis (e.g., data-ink ratios), and the detection of graphical deception.

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Factors Affecting the Development of Graphing Competence

The development of one's graphing competence for communication and decision-making purposes is influenced by multiple, interacting factors. Like any learned practice, students' prior knowledge of and experience with graphing affects their ability to successfully read, interpret, and transform graph data. Common challenges demonstrated in graphing across age groups and levels of expertise as well as potential barriers and opportunities to graph learning for *all* students should be considered for guiding the design and implementation of effective graph instruction.

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[+ Common Challenges Students Encounter in Graphing]

- Learners of all ages - from elementary students to practicing scientists - face challenges in making sense of and using graph data. Despite earlier exposure to graphing, instructors should not assume that college students enter the classroom highly proficient in graphing practice and that attention should be directed to common misconceptions and difficulties that their students may hold.
    - In graph interpretation, college students tend to have difficulties with:
        - Mathematical functions (e.g., slope)
        - Interpreting complex and/or multivariable graphs
        - Identifying (global) trends from discrete (local) data points
        - Data variability (e.g., error bars, dispersion)
        - Understanding general graph layout and design features
        - Making connections to the research question or relevant concepts
    - Common graph construction difficulties include:
        - The appropriate selection of graph type
        - Translating data in numeric form to plotted points that represent variable relationships
        - Proper graph layout
        - Use of informative design features (e.g.,scale).
- Practicing scientists and students "see" graph data differently. Disparities between how experts and novices approach graph reading, interpretation, and construction activities reflect differences in one's knowledge of graph content and data representation practices in the field.
    - Being mindful that others may not approach graphing tasks as they do, instructors should consider the teaching and learning of graphing along a developmental trajectory as students transition from novice- to expert-like behavior over time.
    - To assist the development of more expert like skills, students should be guided through practice how to systematically direct their attention toward salient information when reading a new graph and to think "between" and "beyond" data in graph construction

    - and interpretation by considering the purpose and source of the graph data as well as relevant conceptual and statistical aspects.
- Reflective practices that incorporate graph choice and graph knowledge at every step in graph creation, reading, and interpretation need to be modeled by the instructor and encouraged in the classroom.
    - Students need practice and guidance in reflecting on relevant variables, the best form of the data to plot, understanding the affordances and limitations of graph types, and thinking about the data in the context of the relevant biology and how the data were collected. (see the Design principles link)

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[Article] Glazer, N. (2011). Challenges with graph interpretation: A review of the literature. Studies in science education, 47(2), 183-210. This review examines the importance of graph interpretation competence in the sciences and challenges that science learners encounter when interacting with and interpreting graph data. Drawing on empirical studies conducted with students at the elementary, secondary, and postsecondary levels, the author describes how graph interpretation is affected by several interacting factors: the display characteristics of a graph (e.g., format, type, and visual features like scale, aspect ratios, etc.) and one's prior knowledge of graph content and graphing practices. The author also provides information about misconceptions and difficulties in graph interpretation that learners of varying ages hold, including: confusing slope and height; confusing an interval and a point; conceiving a graph as constructed of discrete points; developing an understanding of graph data presented in class; perceiving that graphs must pass a (0,0) point; interpreting complex line graphs that require series comparison; emphasis on x-y trends leading to incomplete interpretation; and difficulties with interpretation due to inappropriate graph format or visual features (e.g., color, scale, etc.). The effect of instructor knowledge is also reviewed as a potential obstacle to the development of students' graphing competence due to the often-limited expertise and lack of awareness among teachers to the difficulties using graphs in graphing that their students may have. Evidence of the importance of explicit instruction offered frequently and over time at increasingly higher proficiency levels as well as the need for pen-and-paper practice in graph construction for students to learn the conventions and technicalities of graphing is highlighted. Finally, the author concludes by identifying the need for further studies on the development of graph competence, raising teachers' awareness of student difficulties with graphing, and the impact of explicit graph instruction and guidance in science curriculum to help students acquire graphing competences.

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[LSE] **Angra, A., & Gardner, S. M. (2017). Reflecting on graphs: Attributes of graph choice and construction practices in biology. CBE—Life Sciences Education, 16(3), ar53.** In this study, the authors used the meta-representational competence and expert-novice frameworks to design, conduct, and analyze think-aloud interviews to reveal differences in graph construction reasoning and graph quality between undergraduate biology students without research experience (n=10), with research experience (n=5), graduate students (n=15), and professors (n=5) in a pen-and-paper graph construction task. Participants were given either a bacteria or plant growth scenario, both containing a dependent variable, an independent variable, and two treatments with three replicates in each treatment. Simple numbers were provided in a table so participants could easily manipulate the data, if they chose to do so. Inductive analysis revealed that all professors planned and thought about data before graph construction. When reflecting on their graphs, professors and graduate students focused on the function of graphs and experimental design, while most undergraduate students relied on intuition and data provided in the task. Using a qualitative approach to compare the graphs attributes across participant groups, it was noted that most undergraduate students meticulously plotted all data with scaled axes, while professors and some graduate students transformed the data, aligned the graph with the research question, and reflected on statistics and sample size. This study provides targets for undergraduate and graduate instruction in the lecture and laboratory setting.

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[LSE] **Harsh, J. A., Campillo, M., Murray, C., Myers, C., Nguyen, J., & Maltese, A. V. (2019). "Seeing" data like an expert: An eye-tracking study using graphical data representations. CBE—Life Sciences Education, 18(3), ar32.** To examine the cognitive strategies of students and scientists as they read and interpret graphs, the study authors used eye-tracking data supplemented with interview questions . Data were collected from 36 participants of varying levels of scientific expertise (non science majors, early biology majors, advanced biology majors, biology graduate students, and science faculty) as they completed graph-based tasks focused on science-related topics drawn from everyday sources (e.g. medical pamphlets, ecological footprint, sports). Eye movement data were analyzed to examine where, when, how long, and in what order participants directed their attention (i.e. fixations and visual search patterns) at various graph scene elements (e.g., title, variable, and graph data). Study findings highlight variation along the expert-novice continuum as participants with higher levels of expertise allocated more attention toward contextual (i.e. graph title/caption, variables, legend/key, and data source) and graph data features relative to their more novice counterparts. Less experienced participants were also more likely to demonstrate sporadic search patterns and to lack alignment between their intended and actual cognitive strategies when faced with a new graph interpretation task. The authors suggest that explicit instruction using instructional scaffolding to target the differences observed in the study between expertise groups can help novices demonstrate more expert-like practices.

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[Article] **Maltese, A. V., Harsh, J. A., & Svetina, D. (2015). Data visualization literacy: Investigating data interpretation along the novice—expert continuum. Journal of College Science Teaching, 45(1), 84-90.** Motivated by gaps in the literature in understanding how and when students develop graphing proficiencies, the authors developed and tested an instrument to measure differences in how individuals along a continuum of STEM expertise interpret graphical representations. A national sample of adult participants (n=202) with varying levels of academic training – from first-year non-STEM undergraduates (novice) to practicing STEM professionals with an advanced degree (experts) – were recruited to complete the validated online assessment of 20 tasks focused on the reading and interpretation of science-related graphs and tables of varying complexity drawn from everyday sources. Analysis across seven groups (by academic level) found significant differences in the interpretative abilities of expert and novice end-members, with little differentiation between the middle groups (second-year undergraduates to those with a master's degree). A moderate correlation was observed in the relationship between the amount of completed STEM coursework and performance, which in part reflected the difficulties that even participants with higher levels of expertise had with more complex representations (e.g., multi-scaled, those requiring simple calculations). The authors argue that instructors should not assume that undergraduate and graduate students enter their courses with a high proficiency in graph interpretation, and that explicit instruction may be necessary to help develop graphing skills, especially for complex representations that require readers to make connections between data and multiple graph elements.

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[+ Barriers to Developing Graphing Competence]

- Instructor knowledge and awareness as well as access to resources is critical in supporting the development of students' quantitative literacy, including graphing competence.
    - Freely available resources and professional development to improve college instructors' ability to bring together their knowledge of the discipline and ways to teach quantitative literacy would benefit student skills.
    - College instructors need to be aware of common struggles their students have with graphing for teaching and learning purposes.
    - It is not uncommon for pre-college teachers to have limited expertise in graphing, which may influence students' ability to use and understand graphs upon entering the college classroom. Therefore, there is a distinct need for an emphasis to be placed on graphing in teacher preparation programs, such as in science content courses.
- Students encounter graphs in a variety of contexts in their high school and college science courses, including textbooks. This provides students with an inaccurate model of data visualization and nature of biological data and the systems from which they come. Textbooks often present graphs:
    - That lack variability due to the representation of summarized, idealized data
    - Missing axis labels, units, or figure captions that present contextual information to reinforce the data collection methods and other details of measurement and data analysis.
    - Mainly as bar, line, and scatter plots which takes away from exposing students to other types of graphs and data visualizations.
- Graphs found in professional journals are often multivariate plots of messy data, representing the true nature of biological data. However, reviews of figures in science journals reveal that authors often use graphs that fail to effectively report data by choosing inappropriate graph types for the presented data that may obscure variation or have design elements that detract from clear communication.

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[Article] Bowen, G. M., & Roth, W. M. (2005). Data and graph interpretation practices among preservice science teachers. Journal of Research in Science Teaching, 42(10), 1063-1088. As K-12 science reform documents commonly include graph-related actions students should be competent with, the authors of this study examined preservice teachers' interpretation of data and graphs produced from their own inquiry-based investigations. Study participants (n=25) were candidates in a post-baccalaureate program for elementary and secondary science teachers, each having previously earned a science major or minor. In association with guided-inquiry activities in their methods course, participants completed multiple pen and paper data/graph interpretation and transformation tasks that drew on actions comparable to what they would be expected to teach. Through qualitative analysis it was found that preservice teachers had difficulties with structuring data and selecting an appropriate representation. They also had difficulties with random variations in measurement as they held the view that data points must fall "in line" to make claims about variable relationships. While the study was conducted with preservice teachers, the findings highlight three points salient to college science instruction. First, despite having prepartion as science majors and minors, many participants demonstrated difficulties in graph-related practices identified as important for younger students. Second, as argued by the authors, "at present, preservice teachers do not seem ready to teach data collection and analysis in a way suggested by reform documents" (p. 1087). Thus, instructors of introductory science courses should be mindful that incoming students might not yet have received appropriate instruction to develop the graph-related competencies included in secondary reform documents. Third, in benefit to their teaching, study results suggest the need to engage preservice teachers in data representation and interpretation practices through authentic scientific activities.

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[Article] **Roth, W. M., Bowen, G. M., & McGinn, M. K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching, 36(9), 977-1019.** In light of the textbook-oriented approaches to teaching and learning regularly used in secondary science, the authors examined to what degree high school textbooks introduce students to graphing practices required to read scientific texts. The authors conducted two complementary analyses to compare the differences between six representative high school biology textbooks and five ecology-related journals in the graphs displayed and the practices required to read them. Findings revealed that while the overall frequency of inscriptions in the reviewed high school biology textbooks and scientific journals were comparable, the type and nature of the inscriptions used to relay information were notably different. High school biology textbooks predominantly relied on pictorial imagery (photographs, drawings, and diagrams) with fewer graphical models representing general trends, whereas Cartesian graphs of varying types constituted the major inscription type in scientific journal articles. Further comparisons showed that graphs in high school textbooks consistently lacked scales and units of analysis, presented smooth curves that did not reflect statistical variation in real data, and principally featured line and bar graphs. Additionally, scientific journals were found to provide more resources in the caption and main text to assist readers in understanding the featured data and represented relationships. The authors argue that common graphing difficulties reported in the literature for secondary and postsecondary learners may (in part) reflect the observed discontinuities in graph-related practices between high school science textbooks and scientific journals. The authors conclude the article by summarizing this study as part of a larger project on the developmental trajectory of graphing practices, in which they highlight the instructional importance of teaching the reading, interpretation, and production of graphs as an integral part of doing science.

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[Article] Weissgerber, T. L., Winham, S. J., Heinzen, E. P., Milin-Lazovic, J. S., Garcia-Valencia, O., Bukumiric, Z., ... & Milic, N. M. (2019). Reveal, don't conceal: transforming data visualization to improve transparency. Circulation, 140(18), 1506-1518. In response to reported problems with how biomedical data are commonly presented, and corresponding concerns as to the potential impact of poor data displays on health-related decision-making, the authors conducted a systematic review of studies published in prominent vascular disease journals to assess the prevalence of suboptimal visualization processes. Stemming from a review of over 200 papers in 13 journals, the authors identified a set of common visualization problems as well as basic steps investigators can take to correct these data display issues. In particular, the authors focused on the prevalent inappropriate use of bar graphs to present continuous data (observed in approximately half of the reviewed papers) that prohibits readers from critically and effectively evaluating the displayed data. The authors then provide a literature-based primer regarding how to (1) select the correct graphic for the given study design, sample size, and type of outcome variable; (2) effectively present summary statistics that reveals data distribution; and (3) limiting the potential for "mixed messages" in scientific literature by improving the alignment between figure structure with the study goals and design. In support of this, the authors provide a list of free tools and resources to help in the preparation of effective data displays. Of benefit to faculty is that this article can be used both to inform instructional classroom practices as well as the training of future STEM practitioners.

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[LSE] Corwin, L. A., Kiser, S., LoRe, S. M., Miller, J. M., & Aikens, M. L. (2019). Community College Instructors' Perceptions of Constraints and Affordances Related to Teaching Quantitative Biology Skills and Concepts. CBE—Life Sciences Education, 18(4), ar64. In this study, Corwin and colleagues investigated the challenges and affordances of the instruction of quantitative biology (QB) at community colleges. Semi-structured interview data were collected from 20 community college instructors, representing a national pool of institutions with varying levels of student diversity, about their perceptions and experiences teaching QB. Through qualitative analysis, the authors identified six themes of constraints of teaching QB and eight themes for instructional affordances. The authors summarize the instructor-identified challenges under three topics: perceived student-deficit models (in students' math backgrounds), tensions between content coverage and time to teach skills, and teachers' pedagogical content knowledge in QB instruction. These challenges align with those previously-identified for work around the integration of innovative curriculum changes in any college level STEM class. Using the affordance themes and extant literature, several strategies were identified that community college instructors could use or leverage to facilitate QB instruction. Recommendations for professional development opportunities designed to support instructors in QB instruction are provided. As noted by the authors, while the exploratory study was conducted in the context of community college instruction, the presented findings are more broadly applicable as evinced by common challenges for any context and can be leveraged across institutional types to promote change in teaching QB in college biology.

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[Article] Gardner SM, Suazo-Flores E, Maruca S, Abraham JK, Karippadath A, and Meir E (2021) Biology Undergraduate Students' Graphing Practice in Digital versus Pen and Paper Graphing Environments. Journal of Science Education and Technology. Understanding the use of technology to create data visualizations, such as graphs, holds promise for effective teaching and assessing student graphing competence. The authors explored undergraduate biology students' graphing practices with a complicated data set in two different graphing modalities. Participants were provided with a conservation biology scenario and an overarching research hypothesis to evaluate using a data set of relevant and irrelevant quantitative and categorical variables. Participants were randomly assigned to graph the data during a think-aloud interview using either pen-and-paper or using a digital tool called GraphSmarts. GraphSmarts is an assessment tool which builds from previous research on student graphing and aims to constrain and focus students while providing them with a place to explore data and allows their actions to be monitored. While both groups showed difficulties in selecting the relevant variables to plot, students plotting in the digital environment (GraphSmarts) were more likely to select and plot the most relevant variables, leading to higher quality graphs. While not statistically significant, the GraphSmarts allowed for rapid iterations on data exploration and graphing compared to the pen-and-paper environment. This was supported by participants' verbal justifications for their graph type choices. GraphSmarts participants more often stated data exploration as their reason while the ease of construction was the most common justification given by participants graphing with pen-and-paper. Findings from this study demonstrate the affordances and potential limitations of the graphing environment in which students learn and practice graphing which should inform instructor choices for teaching and assessing student graphing competence.

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[Article] Rybarczyk, B. (2011). Visual literacy in biology: A comparison of visual representations in textbooks and journal articles. Journal of College Science Teaching, 41(1), 106. This article compared visual representations from three common sources utilized by a typical biology undergraduate student: general biology textbooks, discipline-specific textbooks, and primary journal articles. Analysis of visual representations from only the main text of the textbook chapters across five different types of textbooks (general and discipline-specific) and 30 articles from seven journal titles revealed five major categories of visual representations: 1) diagrams, line drawings, and computer-generated graphics, 2) graphs/charts, 3) tables, 4) photomicrographs, digital images, and photographs, and 5) gel electrophoresis images. Substantial differences were observed across textbook and journal sources in the visualizations used. In particular, graphs and figures appeared more frequently in journals than in textbooks (general and discipline-specific). Beyond frequency, journal articles were also found to represent data in graphs and figures using a greater variety of display types and with more complexity compared to textbook imagery. More broadly, analysis of end-of-chapter questions showed that discipline-specific textbooks integrated experimental data at a significantly higher frequency than the general biology textbooks, meaning that students at the introductory level of biology had fewer opportunities to practice data analysis skills. The discrepancy in visual representations makes it even more urgent for instructors to not only integrate visualizations from multiple sources but also provide ample opportunities for students at all education levels to engage with experimental data and improve visual and data literacy.

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[+ Inclusive Teaching Practices]

- Instructors can make use of inclusive teaching and learning strategies that support the engagement and achievement of all students to foster the development of graphing competence within their classroom. These general practices include:
    - Incorporating teaching and assessment strategies using contexts that resonate with their student populations.
    - Encouraging a combination of individual participation and strategic collaborative learning.
    - Having students participate in reflective activities.
- Students enter the undergraduate science classroom having extensive prior experience with graphing. The diversity and depth of these experiences can lead to different instructional needs for students in support of their continued development of graph competence.
    - Instructors need to be aware of student graphing abilities and can use early, frequent formative assessment practices to identify areas of improvement and guide teaching practices in response.

- As visual objects, instructor decisions regarding graph design and presentation can affect the accessibility to blind, visually impaired, and colorblind students.
    - The use of freely available resources to guide design choices (e.g., color selection) and to provide accessible data displays (e.g., tactile graphics) can remove barriers for these students.
    - Simple strategies can improve how all students engage with visual data, but the effects are disproportionately greater for visually impaired students. These include explicit verbal descriptions, peer instruction, using alternative models (e.g., physical modeling), and varying assessments of competencies.

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[Article] Stone, B. W., Kay, D., & Reynolds, A. (2019). Teaching Visually Impaired College Students in Introductory Statistics. Journal of Statistics Education, 27(3), 225-237. As classroom instruction and supporting resources in postsecondary STEM courses relies heavily on visual information (e.g., graph data, instructor gesturing, textbook diagrams), blind and visually impaired (BVI) students often face access barriers to building foundational statistical skills. This review explores the challenges of teaching statistics to BVI students and provides a variety of accommodations informed by research in cognition and learning. Here, considerations relevant to graphing are highlighted, but the article also examines aspects of teaching statistics to BVI students (e.g., use of equations, analysis of data sets), that are relevant for biology instructors given the quantitative nature of the field. Within the classroom context, accommodations related to instructor behavior (explicitly verbalizing what is shown in presented graphs and how to interpret) and the use of collaborative problem solving with sighted peers to help make graph data more accessible to BVI students are outlined. Outside the classroom, a variety of accommodation ideas for teaching BVI students to create and interpret graphs are discussed (e.g., being attentive to the accessibility limitations of online/digital homework systems, making resources available during an exam that students have practice with). The strengths and weaknesses of varying types of auditory and tactile learning aids (i.e. tactile graphics, hands-on education models, 3D printing) are also reviewed as an evidence-supported means to engage BVI students with data. The authors conclude the article noting that a combination of strategies and resources will likely be necessary to accommodate BVI students in learning quantitative skills at the college level. Additionally, the employed strategies should be guided by extensive student-instructor communication and considered on a case-by-case basis as, like all learners, what may work for one student may not work for another. The considerations and approaches outlined in this article in the context of supporting BVI students represent responsive and inclusive practices that would likely support all students in the creation and reading of graphs.

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[Article] Jones, J. L., Jones, K. A., & Vermette, P. J. (2011). Planning Learning Experiences in the Inclusive Classroom: Implementing the Three Core UDL Principles to Motivate, Challenge and Engage All Learners. Electronic Journal for Inclusive Education, 2(7), 6. This essay explores the use and interplay of two curriculum and instructional decision-making frameworks for the intentional development of learning experiences that allow all students opportunities for success. The authors first outline the planned learning experience (PLE) framework that guides teachers through a four-part structure to help them apply differentiated instruction by considering student needs and the management of learning interventions and assessments to facilitate individual growth. The Universal Design for Learning (UDL) framework, an approach to optimize equal learning opportunities for all students, is then introduced focusing on the three principal interrelated design features that includes providing students multiple means of representation, action and expression, and engagement. The authors synthesize the core principles of these two frameworks to provide general guidance in applying an integrated UDL supported lesson planning model. The article concludes with an example case-study based statistics lesson (that includes graphing) to demonstrate how the two frameworks can benefit inclusive instructional practices. While the presented lesson is intended for 7th grade mathematics students, the discussion and application of the core PLE and UDL features can be broadly applied to topics in the K-16 classroom.

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[Resource] Levine, A. (2019) True Colors: Optimizing Charts for Readers with Color Vision Deficiencies. As 8 percent of males and 0.5 percent of females are color blind (color vision deficiency), instructors and researchers should consider the use of barrier-free colors in graphs and other data visualizations when preparing learning materials and scholarly articles. This webpage from Wichita State University highlights general principles to design accessible visualizations as well as additional supporting resources, links to color blindness simulators to test figures, and step-wise examples on how to address sample problematic graphs.

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[Resource] Describing Science Images for Learners with Disabilities. This site from the National Center of Accessible Media (NCAM) provides guidelines drawn from NSF funded research for the presentation of visual STEM information to blind and visually impaired students and scientists. Examples as to how the general guidelines can be implemented across a range of visualization types (e.g., scatter plot, line graph) are provided.

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[Resource] Color Oracle. This site provides a free software tool that allows users to quickly see how figures may look to a person with common colorblindness impairments: deuteranopia, protanopia and tritanopia. The colorblindness simulator is available in Windows, Mac and Linux formats.

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[Resource] **Braille Authority of North America (2010). Guidelines and Standards for Tactile Graphics.** This link offers guidelines provided by the Braille Authority of North America and the Canadian Braille Authority to standardize best practices for the use and creation of braille and/or tactile graphics for visually impaired tactile readers. The 12-part online training manual provides information and guidelines across a range of topics for educators and others, including recommendations for the design of tactile mathematical and scientific diagrams.

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[Resource] Tanner K (2013) Structure Matters: Twenty-One Teaching Strategies to Promote Student Engagement and Cultivate Classroom Equity. CBE-Life Sciences Education 12(3). This practical guide provides a summary of some of the best practices for equitable teaching practices and advocates for a purposeful management of the learning environment to foster student engagement and sense of belonging. Many of these techniques will be useful in supporting and inviting all students to learn graphing by supporting their individual thinking and reflection, strategies for eliciting diverse ideas and perspectives, managing to classroom to model the social practice of science, including graphing.

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[Guide] Inclusive Teaching**.** This evidence-based teaching guide provides a broad framework of research literature and resources that can help instructors develop self-awareness and empathy toward others, create a supportive classroom environment, and utilize inclusive teaching practices in the college science classroom to provide all students opportunities for success.

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[Resource] CAST Universal Design for Learning (UDL) Guidelines . This website provides guidelines to the implementation of Universal Design for Learning (UDL), described as a framework to improve and optimize teaching and learning for all learners based on scientific insights. The guidelines offer a cross-domain set of evidence-based recommendations that can be broadly implemented by educators, curriculum developers, researchers, and parents. The concrete UDL guidelines focus on three aspects of learning, including engagement (interest and motivation), representation (information presentation), and action and expression (activity and assessment).

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Measuring Graph Competence

Following the principles of backward design allows instructors to have clearly identified targets for student learning and define strategies for capturing evidence of that learning and development of competence. As such, articulating cognitive and non-cognitive learning outcomes and using assessments aligned with them allows instructors to then design learning experiences for students.

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[+ Learning Outcomes for Graph Instruction]

- Similar to concept-oriented learning objectives and other complex practices, instructors should clearly identify and articulate measurable learning outcomes for graphing skills that will guide assessment and teaching practices in development of student competencies. Defined learning outcomes are an inclusive means to explicitly communicate student expectations and unpack subcomponents of complex disciplinary practices such as graphing.
- Consensus documents (e.g., Vision and Change) and validated frameworks (e.g., BioSkills Guide) provide broad targets for a competency-based approach to the instruction of graphing skills from which instructors can develop more targeted objectives relevant to their course and student contexts

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[LSE] **Clemmons, A. W., Timbrook, J., Herron, J. C., & Crowe, A. J. (2020). BioSkills guide: Development and national validation of a tool for interpreting the Vision and Change core competencies. CBE—Life Sciences Education, 19(4), ar53.** The 2011 Vision and Change consensus report for undergraduate biology education articulated sets of core concepts and competencies in biology to guide instruction and assessment of student learning. The BioSkills Guide expands the broadly described Vision and Change core competencies by outlining what they mean to undergraduate biology majors (specific activities and knowledge) as well as providing measurable learning outcomes that students should be able to complete prior to graduation. The authors engaged in cycles of drafting, validity evidence collection, and revision to produce a set of competencies that reflected the priorities and practices of a diversity of undergraduate biology instructors and student populations, institution types, course level, and biology subdisciplines from across the United States. This validated competency set includes creating and using data visualizations, including graphs, in the areas of Quantitative Reasoning (create and interpret informative graphs and other visualizations) and Process of Science (analyze data, summarize resulting patterns, and draw appropriate conclusions). This is a valuable starting point for instructors and researchers who wish to document and improve student graphing practices in the context of biology.

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[Article] **Pelaez N, Gardner SM, & Anderson T (2022). The problem with teaching experimentation: Development and use of a framework to define fundamental competencies for biological experimentation. Trends in Teaching Experimentation in the Life Sciences, Editors, Nancy Pelaez, Trevor Anderson, and Stephanie M. Gardner, Springer publishing.** Experimentation is one process by which new knowledge is generated and involves an ongoing and cyclical set of activities. In an effort to guide instruction and assessment of experimentation competence by undergraduate biology students, the ACE-Bio Network (Advancing Competence with Experimentation in Biology) has broken experimentation in biology into 7 competency areas each with several concept-skill statements. These competencies for biological experimentation emerged from the collaborative work between practicing basic science researchers and biology education specialists with expertise in biology and biology teaching and education research. The seven competency areas are (in no particular order): plan, analyze, conduct, question, communicate, identify, and conclude. The use of visualizations, including graphs, is woven throughout the competencies with particular emphasis in using data visualizations in the planning of investigations and during data analysis and communication. Within these areas are concept-skill statements that can be used to frame learning objectives to guide teaching and assessment. These concept-skill statements are at a fairly large grain size in need of elaboration, but serve as a valuable starting point for instructors and researchers involved in teaching and evaluating student competence with graphing.

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[Article] **Aikens, M. L., & Dolan, E. L. (2014). Teaching quantitative biology: Goals, assessments, and resources. Molecular Biology of the Cell, 25(22), 3478-3481.** An overview for the teaching of quantitative biology using a backward design framework where overarching learning goals and assessment strategies are considered prior to the selection of instructional practices is the proposed framework provided by the authors of this essay. Aikens and Dolan begin by outlining goals for teaching quantitative biology, in which they argue for the importance of developing students' cognitive quantitative skills in parallel with positive attitudes towards quantitative work in support of desirable behavioral outcomes (e.g., engagement in learning activities, completion of quantitative degree programs). Here, the authors highlight seven attitudinal goals that emphasize the promotion of students' interest, perceptions (relevance, importance), self-efficacy, and emotional response in quantitative work as well as increased intentions to pursue further coursework or careers in the field. Next, the authors discuss the key role of assessment aligned with identified learning goals in documenting the impact of quantitative biology instruction, and then go on to highlight existing measurement tools as well as formative assessment techniques (e.g., metacognitive prompts) for this activity. Finally, the authors provide examples of varying published curricular approaches to teaching quantitative biology in introductory and advanced courses as well as web and journal resources for interested instructors. Aikens and Dolan conclude the essay by calling for collaborations between education specialists and quantitative biologists in designing and testing assessment tools and instructional resources.

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[Guide] Writing and Using Learning Objectives**.** This evidence-based teaching guide outlines a framework as to how instructors can design learning objectives in support of teaching and student learning.

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[Resource] **AP Biology Course and Exam Description.** The AP Biology curriculum framework explicitly focuses on six science practices to develop skills fundamental to the discipline (pages 190-191). Three of the practices (Visual Representations, Representing and Describing Data, and Statistical Tests and Data Analysis) highlight skills relevant to graphing (see pages 190-191), with clearly defined competency benchmarks provided as well as sample instructional activities to demonstrate how these practices can be integrated with general biology course content. This framework may be of particular use to instructors in designing introductory majors and nonmajors courses.

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[+ Identifying students' strengths and areas of improvement]

- Rubrics are effective tools to assess student graphing skills as well as to guide targeted instruction in the display and interpretation of graph data. An inclusive teaching practice, rubrics clearly communicate expectations and offer students the opportunity for self-assessment.
- Instructors should align their instructional goals with assessment design, which plays a critical role in the effective measurement of graphing skills.
    - Closed response graphing tasks, such as multiple choice questions in concept inventories, are useful in measuring granular, targeted practices (e.g. identifying a data trend) and are easy to grade; however, they are limited in lending insight to students' higher order graph thinking.
    - Open-ended tasks, while more laborious to evaluate, can engage students in authentic graphing practice in the context of data analysis as well as readily reveal their decision-making and reasoning in the use and display of graph data.
- Authentic assessments provide students the opportunity to demonstrate their competence through "real world" tasks valued in their own right within the field of practice. Within biology, authentic measures of students' graphing skills would often occur in the context of data analysis and communication during scientific inquiry or experimentation.
- Providing students with opportunities to reflect as they are graphing can reveal the underlying reasoning involved in their responses and products and help point instructors to important instructional areas of need. Reflections can be easily incorporated within formative and summative assessments. (cross reference Designs in Action and DU)

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[Article] Wiggins, G. (1990) "The Case for Authentic Assessment," Practical Assessment, Research, and Evaluation: Vol. 2 , Article 2.

This brief essay outlines the importance of authentic assessment practices in measuring student competencies. While the article is written about general assessment practices in education, the discussion to the value and design of authentic assessment (direct measures of one's performance in completing intellectually challenging tasks) compared to traditional assessment (those that rely on indirect "proxy" items to gauge proficiencies) is relevant with how instructors can effectively evaluate students' graph competencies. In particular, the author highlights several technical considerations for developing authentic assessments, including: (a) requiring students to use prior knowledge (e.g., disciplinary, graphing, contextual) in completing tasks, (b) engaging students in tasks that align with the priorities and challenges of the discipline, (c) involving complex or “ill-structured” tasks comparable to or in practice of the types of real-world problems faced by practitioners, (d) providing students “open” space to provide thorough and justified responses, and (e) achieving validity and reliability by identifying and standardizing appropriate criteria for scoring varied responses (e.g,. rubrics). The author concludes the essay by providing an argument as to how the benefits of high-quality assessment (e.g., direct insight into student abilities to improve performance, increased “test validity”) offsets perceived limitations (i.e. time and energy).

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[Article] Berg, C., & Boote, S. (2017). Format effects of empirically derived multiple-choice versus free-response instruments when assessing graphing abilities. International Journal of Science and Mathematics Education, 15(1), 19-38.

In this paper the authors investigate the ways in which the format of an instrument to measure students’ graphing skills can influence the test’s validity. To address this question, the authors studied the responses of 736 7th-12th grade students to three multiple choice (M-C) or free response (F-R; graph drawing) items situated in common kinematic scenarios and data sets. Six versions of the instrument were used in the study, which, in addition to item format (open or closed), varied by the presence/absence of an included (a) drawing of the scenario, (b) written description of the scenario, and (c) instructions to add marks to demonstrate data transitions. Results indicated that the item format of the graphing instrument can significantly affect student responses, influencing measurement validity. Based on multiple lines of evidence, as well other preexisting work, the authors conclude F-R items that ask participants to represent data provide a more valid measure of graphing skills than M-C instruments, which were found to be highly limited in their ability to effectively assess graphing competence. The authors further point out that M-C measures lead to issues with testing fairness as “low classroom performers” are often primed to select responses associated with graphing misconceptions, and F-R assessments offer a more valid and productive measure of their graphing knowledge and competence.

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[LSE] Stanhope, L., Ziegler, L., Haque, T., Le, L., Vinces, M., Davis, G. K., ... & Overvoorde, P. J. (2017). Development of a biological science quantitative reasoning exam (BioSQuaRE). CBE—Life Sciences Education, 16(4), ar66.

The effective assessment of quantitative skills is integral for guiding pedagogical and programmatic decisions to support students in honing and developing competencies essential for success in the sciences. This article focused on the development and validation of the Biological Science Quantitative Reasoning Exam (BioSQuaRE) assessment, a discipline-specific measure, designed in line with recommendations from national reform documents, to provide feedback on college biology students’ quantitative skills. The article reports on the BioSQuaRE instrument and details the multistep, iterative instrument design and testing process used to serve as a model for others hoping to develop similar tools. The final instrument, available to instructors upon request, consists of 29 multiple choice items, of which approximately half contain a graph in the task or response options. Analyzing student test data (n=555) collected from five different institutions of varying types (e.g., public/private, mission), the authors found the tool was able to assess quantitative skills in a biological context for students with a wide range of abilities. The authors conclude the instrument has a range of potential applications, including: measuring changes in introductory students quantitative skills to inform curriculum choices, as a diagnostic tool to identify student quantitative areas of improvement, and programmatic assessment.

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[LSE] Deane, T., Nomme, K., Jeffery, E., Pollock, C., & Birol, G. (2016). Development of the statistical reasoning in biology concept inventory (SRBCI). CBE—Life Sciences Education, 15(1), ar5.

Statistical reasoning, the way one reasons with statistical ideas (e.g distribution, variability) and makes sense of numerical data, is widely recognized as a competency needed to succeed in scientific endeavors and to navigate varying data forms encountered everyday. Further, statistical knowledge and reasoning are important in the creation and reading of graphs of biological data. This article outlines the development and validation of the Statistical Reasoning in Biology Concept Inventory (SRBCI), an assessment which aims to capture undergraduates' conceptions in statistical reasoning specific to biology experimentation. Contextualized in experimental scenarios, the 12-item multiple-choice tool was designed to permit instructors to easily characterize their students' statistical reasoning skills to identify potential learning areas for targeted instruction and to document conceptual gains resulting from curricular innovations. Within an expert-novice paradigm, the authors focused the measure on four core themes that reflect non-expert-like conceptions in statistical reasoning commonly held by undergraduates, including: (1) variation in data, (2) repeatability in results, (3) hypotheses and predictions, and (4) sample size. The authors found that the SRBCI is effective for assessing students' conceptual ability in statistical reasoning in populations of students at different stages of their degree program. Further, the authors contend that performance on the individual concept inventory items provide preliminary insight on students' transition towards more expert-like thinking during their undergraduate training, which may be of interest to other education researchers as well as faculty and administrators seeking to assess programmatic effectiveness. The authors conclude that the SRBCI can provide instructors useful information relating to students' scientific reasoning conceptions and inform the design of teaching interventions in promotion of statistical reasoning in biology, an important part of creating and reading graphs.

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[LSE] Angra, A., & Gardner, S. M. (2018). The graph rubric: development of a teaching, learning, and research tool. CBE—Life Sciences Education, 17(4), ar65.

This article fills an assessment gap in graphing by describing the multi-step development of an evidence-based analytic graph rubric designed to facilitate the teaching and evaluation of graphs, provide formative and summative feedback to students, and allow education researchers to evaluate graphing artifacts. The rubric is informed by literature from the learning sciences, statistics, and representations literature as well as feedback, use, and validation of the rubric by a variety of users (undergraduate students, graduate students, education researchers, and biologists). The rubric consists of categories essential for graph choice and construction: graph mechanics (descriptive title, axes labels, units, scale, and key), graph communication (aesthetics and take-home message), and graph choice (graph type, data displayed, and alignment to the research question and hypothesis). Each category of the rubric can be evaluated at three levels of achievement (excellent, present but needs improvement, and absent or inappropriate). The graph mechanics are weighted less than the other two categories due to lack of cognitive difficulty. The rubric has the potential to provide formative feedback to students and allow instructors to gauge and guide learning and instruction.

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McKenzie, D. L., & Padilla, M. J. (1986). The construction and validation of the test of graphing in science (TOGS). *Journal of research in science teaching*, *23*(7), 571-579.

This article explains the creation and validation of a multiple-choice test of graphing skills (TOGS), specifically line graphs, for science students in grades 7-12. Nine learning objectives were developed and included skills that are important for either construction or interpretation of line graphs. Examples of skills that learning objectives were aiming to assess were: selecting appropriate axes, locating points on a graph, drawing lines of best fit, interpolating, extrapolating, describing relationships between variables, and interrelating the data displayed on two graphs. Fourteen multiple-choice items were written for the five learning objectives aiming to assess graph construction. Twelve multiple-choice questions were written for the four learning objectives aiming to assess graph interpretation. The questions themselves did not include any scientific concepts or jargon, but everyday variables like the amount of gasoline used for a trip. Content validity was established by having experts review and score the questions. Reliability coefficients of 0.81 and 0.83 indicate that TOGS is a reliable and valid test.

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[Resource] Gormally, C., Brickman, P., & Lutz, M. (2012). Developing a test of scientific literacy skills (TOSLS): Measuring undergraduates' evaluation of scientific information and arguments. CBE—Life Sciences Education, 11(4), 364-377.

This resource is an article on the development, testing, and validation of the Test of Scientific Literacy Skills (TOSLS). We recommend this article for readers who are interested in assessing introductory students' skills related to major aspects of scientific literacy (recognizing and analyzing the use of methods of inquiry that lead to scientific knowledge and the ability to organize, analyze, and interpret quantitative data and scientific information), which includes several graph-based tasks.

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Designing Graphing Activities

Graphing is a learned practice that requires the effective application and integration of concepts and skills from multiple domains (e.g. biology, statistics, cognitive science, and visual perception) in order to represent and make sense of complex biological phenomena. Instructors can support the development of these skills by providing students directed guidance and opportunities to practice reading, interpreting, drawing, and evaluating graph data. In this section of the guide, six design considerations for effective graph teaching and learning are focused on: (a) teaching graphing in the discipline, (b) explicit graph instruction, (c) the use of real-world “messy” data, (d) engaging students with meaningful data, (e) collaboration, and (f) reflective practices. Each of the detailed design features have been reported to contribute to students’ graphing skills, with the potential for additive effects when used jointly given the diverse cognitive processes involved in making and using graphs (i.e. “some is good, more is better”).

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[+ Teaching in the Discipline]

- Graphing is a practice ubiquitous across fields that is bound by the specific practices and norms in the collection, analysis, and communication of the discipline from which the data arise. It is important for instructors to engage biology students in contextualized activities that reflect the graphing conventions as well as the inquiry practices and priorities of the community.
- Teaching graphing in disciplinary contexts not only strengthens graphing competence but also promotes disciplinary concept and skill learning.

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[Article] Bowen, G. M., Roth, W. M., & McGinn, M. K. (1999). Interpretations of graphs by university biology students and practicing scientists: Toward a social practice view of scientific representation practices. Journal of Research in Science Teaching, 36(9), 1020-1043. The authors define a framework based on the perspective of graphing as a social practice instead of an information processing, cognitive skill perspective. This framework consists of 5 domain-specific areas to capture the degrees of purposeful participation graphing practices. Ten undergraduate students in a second-year ecology class along with six experimental and theoretical scientists from the fields of ecology and physics participated in this study. All participants were asked to interpret a graph depicting birth/death rates as a function of population size and how it will inform species conservation efforts. Student data were gathered in a small group setting to capture the group construction of understanding during a seminar discussion followed by a small group interview to discuss an exam question which involved a similar task. Experimental scientists interpreted and discussed the same graphs during an unstructured interview. The scientists approached the task differently from each other, drawing on resources related to their expertise. While the theoretical ecologists were able to draw more from ecology knowledge, they approached the task in a similar way to the theoretical physicist; they both focused on the graph-mathematical model transformations with little regard to the underlying ecology concepts. In contrast, the two experimental ecologists instantiated the graph with specific examples to make sense of it as it relates to conservation. By comparison the undergraduate ecology students exhibited several breakdowns in making sense of the graph (and a similar one on an exam) which was a reflection of their developing domain-specific knowledge from which to draw examples and apply relevant concepts (e.g. rate vs. density vs. population size). This paper emphasizes the need to teach the concepts and practices of a discipline together with the representations of the domain.

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[Article] **Konold C, Higgins T, Russell SJ, Khalil K (2014) Data seen through different lenses. Educational Studies in Mathematics 88 (3), 305-325**. This study describes the ways in which pre-college students view the nature of data and how they work with it. The nature of students' reasoning about data were derived from three data sources collected as part of qualitative studies conducted within mathematics and statistics education intervention programs for K-12 learners. The authors identified four different perspectives that students use when interpreting data: pointers, case values, classifiers, and aggregate. Pointers refer to perspectives on data in which the data and the larger event from which the data originate are not differentiated. Case values perspectives involve describing data based on attributes of a single case in the data set. Classifier perspectives involve providing information about the frequency of certain observed case types. Finally, the data as an aggregate perspective refers to the perceptual unit being the entire data distribution with features that are not specific to any single value in the distribution. While there is a suggested hierarchy across data perspectives, with younger students tending to have data perspectives on the lower end of the hierarchy, this does not mean that there is a progression of preferred data perspectives to some higher level. Depending on the purpose and context, different data perspectives are appropriate; there is no one single correct form. Different perspectives on data have implications for both graph construction and interpretation. Data perspective has a strong influence on how a data display is selected and what comparisons are represented. Further, interpreting a graph could be influenced by the viewer's data perspective which could be different from the graph creator's intent.

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[Article] **Åberg-Bengtsson, L., & Ottosson, T. (2006). What lies behind graphicacy? Relating students' results on a test of graphically represented quantitative information to formal academic achievement. Journal of Research in Science Teaching, 43(1), 43-62.** This study describes the construction of a test of graph interpretation as well as the identification of factors that may be important to consider when teaching and evaluating secondary students' graph interpretation. The authors design a graph interpretation test using a set of 18 graphics comprised of line graphs, scatter plots, bar graphs, and cartograms. The contexts for the data and graphics were drawn from textbooks the students used in classes and scenarios of everyday experiences that would be relatable to the students. Question types were multiple choice interpretation or reading tasks in which students had to read off a value from a graph and write it down. Students in the ninth grade from 5 different schools in Sweden completed the test and academic achievement data were gathered (n = 355 students). Knowledge of graphs and what they are used to depict, and the mathematics knowledge needed to extract values and understand the data displayed were important factors in students' performance on the assessment. However, knowledge and familiarity with the context and content of the data and the scenario from which they arose were perhaps more critical factors, even with experts. This has implications for the teaching graphing to students and interpreting students' competence with graph interpretation if the content and context of the data are not well-known to the students.

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[Article] **Xiong, C., Van Weelden, L., & Franconeri, S. (2019). The curse of knowledge in visual data communication. IEEE transactions on Visualization and Computer Graphics, 26(10), 3051-3062.** This study examines a well-documented psychological phenomenon in language and decision making called the 'curse of knowledge' within the context of noting data trends in a graph. Undergraduate student participants were told one of several back-stories related to a study whose data were displayed in a graph. Graph data were closely aligned and salient to information given in one of the backstories. In one part of the study, participants who were given the backstory were asked to rank salient features and also predict what the other participants would find most important in the graph. Participants were instructed to ignore the information they knew, reflecting on what they felt would be obvious to any viewer of the graph. The informed participants predicted that others lacking the contextual information would note the same trends they did, which proved to be false. The assumption that general patterns would be innately observed in the data underscores the need to provide well-designed graphs with contextual features (e.g., graph title/caption, variable labels, color cues, etc.) which align the reader and graph creator to appreciate the important features of the graph. This study adds to the growing knowledge around the impact of viewer's prior familiarity with the content on their ability to generate inferences from data in graphical formats resulting from top-down processes in graph comprehension. Even seemingly simple graphs can lead to divergent readings and interpretations by views depending on their familiarity with the system under study.

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[+ Explicit Instruction]

- Students should be engaged in step-wise approaches to the creation, reading, interpretation, and evaluation of graphs that systematically deconstructs and highlights the relevant actions essential to effective graphing practices.
- Instructors should explicitly model their processes in reading, interpreting, drawing, and evaluating graph data encountered in instruction to allow students to observe how graphing tasks can be approached.
- Graph construction and computer-aided data visualization are distinct cognitive processes that should be instructionally decoupled to benefit student graphing skills.
    - When displaying graph data, students should (1) formulate a design plan to "best" represent the data, (2) sketch the graph by hand to conceptualize and manipulate the design for effective data communication, and then (3) use technological tools to visualize data relationships for interpretive purposes.
- Frequent opportunities and time should be provided to students to acquire and practice graphing skills in the context of problem solving that, if possible, lends exposure to differing data and representation types.
- To help students develop graphing skills, scaffolded learning activities should be utilized over time and involve increasingly complex graphing tasks.

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[Article] Schultheis, E. H., & Kjelvik, M. K. (2015). Data nuggets: bringing real data into the classroom to unearth students' quantitative & inquiry skills. The American Biology Teacher, 77(1), 19-29. In support of instruction connecting science and mathematics for developing students' quantitative and science process skills, the authors outline the intent, design, and use of Data Nuggets in the classroom. Data Nuggets, a freely available online resource for K-16 educators, engages students in exploring a real-world problem using authentic scientific data generated by science practitioners. Approximately one hundred Data Nuggets (at the time of summary writing) of varying reading and graph proficiency levels are posted to the author described online collection (http://datanuggets.org/search-current-data-nuggets/), with topics spanning a range of biological problems (e.g., gene expression, climate change, evolution). Utilizing a case-based design, each Data Nugget models an approach for the explicit instruction of graphing that guides students through a problem by providing (a) relevant contextual information (i.e. background knowledge on the topic and the process of the researcher who developed the experiment), (b) the scientific question and testable hypotheses, (c) data to address the scientific question and to generate a graph as a form of evidential support, (d) practice interpreting graph and tabular data, and (e) the opportunity to draw conclusions and propose future steps to extend the research. The article concludes with a discussion as to how the learning intervention attends to recommendations made in national reports (e.g. Vision and Change) and can be implemented by instructors.

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[Article] Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. Educational psychology review, 14(1), 47-69.of-Class Graphing Activities Increases Student Engagement and Learning Outcomes. Journal of microbiology & biology education, 18(3). This review article summarized the cognitive science research literature up to the time of its publication, ending with an evidence-based list of implications for instruction for improving student competence with graph comprehension. Three areas were examined in particular: (1) visual features of the graph, (2) viewers' knowledge of and about graphs, and (3) viewers' knowledge about and expectations of the data depicted in graphs. The authors make nine recommendations for graph design as well as four additional recommendations for graph instruction. The first is to teach graph reading in the context of the relevant discipline rather than in an abstract context, which allows students to apply their disciplinary and graphing knowledge as well as learn how graphs can be used to critically evaluate data. The second is to have students examine the same data in different representations. This can help students realize how graph design can influence one's interpretation and assist with forming connections between the presented data and effective visual display features. The third is to explicitly focus on the links between visual features in the graph and the meaning that they have to the actual phenomena from which they came. This activity promotes better sense-making by minimizing the abstract nature that the data may take on in the context of the graph, which does not always directly translate to the actual variables in reality. Finally, the authors recommend that instructors make graph reading metacognitive as well as an act of retrieving facts or data points from a representation. Students should be encouraged to approach reading graphs as an interpretation and evaluation task as well as to reflect on their own knowledge and expectations and how this affects their ability to read a graph.

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[Article] Dennen, V. P. (2004). Cognitive apprenticeship in educational practice: Research on scaffolding, modeling, mentoring, and coaching as instructional strategies. Handbook of research on educational communications and technology, 2(2004), 813-828. One of the ways in which students can move from novice- toward expert-like competencies is through interactions with and/or guidance from others (e.g., instructors, peers, etc.) with more advanced experience. This approach builds on the social constructivist tradition that learning is a socially negotiated process and can formally take place in apprenticeship-like models. In the context of learning concepts and the development of intellectual skills, this is termed a cognitive apprenticeship as novice learners complete authentic tasks situated in the field of practice under the guidance of a more experienced mentor. Of particular importance to cognitive apprenticeships is that the ultimate goal is for a learner to progress to a practitioner of the application of the knowledge and skills under study, not merely a knowledgeable observer. As such, there is a progression of expertise development through the use of several methods - or framework - aimed at supporting and guiding the learner, making tacit knowledge and practice explicit and visible. These methods include: (1) modeling thinking processes, (2) explaining the rationale behind activities, (3) coaching to monitor and support students when needed, (4) scaffolding to support students heavily at first and fading as they become competent, (5) having students metacognitively reflect on their own knowledge and performance, (6) having student articulate into words the conclusions of their reflections, and (7) letting the students explore new ideas related to the knowledge being learned. The article elaborates further on each of these methods, providing links to learning theory and evidence from practice. Given the complexity and nuances in creating, reading, and interpreting graphs, the cognitive apprenticeship model provides a useful teaching model for supporting students as they become part of the community of competent practitioners and educated citizens.

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[Article] Patterson, T. F., & Leonard, J. G. (2005). Turning spreadsheets into graphs: An information technology lesson in whole brain thinking. Journal of Computing in Higher Education, 17(1), 95-115.
Graph creation requires the graph maker to engage in analytical thinking to accurately analyze a dataset, select appropriate data to transform, provide correct labels , and draw logical conclusions. Additionally, the graph creator must also interject artistic, holistic, and creative thinking to create a compelling picture of data in the reader's mind. To assist students in learning how to navigate the multiple cognitive processes needed to translate raw data into effective displays, the authors suggest a three-step graphing process. First, students need to select the data of interest, understand relevant statistics, develop a message to communicate, and physically sketch a graph on paper. Second, students should be shown examples of appropriate and inappropriately constructed graphs generated by visualization software (e.g, Microsoft Excel) with explicit discussion around graph type selection, aesthetic criteria, and how to use the software to generate graphs. Third, for visualization purposes, students then use the software for graph creation. An example intervention of these steps is discussed in which students explored the data prior to considering how to communicate it. In the year prior to the "whole brain" data transformation activity, students made many types of common analytical (e.g., selecting the appropriate graph type) and aesthetic (i.e. "look and feel") errors. Following the teaching intervention, in a later semester with a separate student population, the authors noted a decrease in prevalence of the previously identified errors. The authors further report that students generally demonstrated a deeper understanding of data transformation in Excel and showed a greater appreciation of the emphasis on the visual message in comparison to their earlier counterparts that did not participate in the intervention.

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[+ Use Data Meaningful to Students]

- Activities that include graph data meaningful to students can benefit motivation, promoting engagement and learning. Instructors can support student motivation through scaffolded instruction by:
    - Providing opportunities for students to collect and analyze self-generated (or first-hand) data.
    - Allowing students ownership in selecting existing (second-hand) data to explore and analyze. Scaffolded learning activities with second-hand data should prompt students to understand the nature and purpose of the provided information.
    - Using problems or contexts that connect students to the data based on relevance or potential interest.

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[Article] **Renninger, K. A., & Hidi, S. E. (2021). Interest development, self-related information processing, and practice. Theory Into Practice, 1-12.** Drawing on findings from research literature in psychology, education, and neuroscience, the article explores the centrality of interest in learning, and how educators can support students' interest development. This focus stems from the position that interest, one's willingness to engage with content, is both a cognitive and affective motivational variable that benefits attention, goal setting, sustained engagement, and performance. Specifically, the authors argue to the instructional value of helping learners identify self-related connections to the content (or self-related information processing) in benefit to their interest development by (a) triggering interest, which encourages learners to seek out further information and persevere in understanding material, or (b) deepen the interest through sustained engagement for those with existing interests. In explanation to the importance of supporting interest development, the authors summarize previous studies from various content areas and learning settings regarding the benefits of interest on learning for learners of all backgrounds. The Four-Phase Model is shared for distinguishing learners' developing interest from (1) triggered situational interest to (2) maintained situational interest to (3) emerging individual interest to (4) well-developed individual interest, with evidence-based insight as to how instructors can help cultivate student interest by phase. The authors additionally provide background on self-related information processing, highlighting the benefits when learners work with personally relevant content to increase engagement and activation of the reward circuitry in the brain. Allowing students to generate meaningful personal connections with the content promotes interest as well as sustains opportunities to advance conceptual understanding. For example, student use of data of interest to them could promote stronger interest in learning graphing and related concepts. The article concludes with a discussion of general instructional implications, which can be readily considered through the lens of promoting student motivation in developing data representation skills.

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[Article] DeBoy, C. A. (2017). Student Use of Self-Data for Out-of-Class Graphing Activities Increases Student Engagement and Learning Outcomes. Journal of Microbiology & Biology Education, 18(3). In this article, the author investigated how differences in data acquisition (i.e. self-generated versus instructor provided) affected the learning and engagement of students in a 200 level "biology of women" capstone course for biology majors and non-majors at a historic women's college. During a unit on hormonal regulation, students were separated into two treatment groups differing in data acquisition on basal body temperature, in which one group was provided data by the instructor and a second collected self-generated data based on their own reproductive cycle (30 continuous days of data collection). All students were trained to collect pulse and stress-level perception data. To assess if the mode of data affected learning, students were assessed three times over the semester: after a lecture on hormones but before a graphing activity, after a graphing activity, and on the final exam. Comparisons of direct (quizzes) and indirect measures (surveys) for students using self-generated versus provided data suggest that while both activities increase learning outcomes, use of self-data compared with provided data has a greater impact on increasing learning outcomes and enhancing confidence in graphing skills and graphing efficacy.

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[Article] Hug, B., & McNeill, K. L. (2008). Use of First-hand and Second-hand Data in Science: Does data type influence classroom conversations?. International Journal of Science Education, 30(13), 1725-1751.
Increased availability of public datasets provide students with opportunities to increase their understanding of diverse phenomena by exploring data that they may be unable to gather in standard K-16 classrooms. However, it is unclear how working with these second-hand data are similar or different to working with self-generated data (first-hand data) as it relates to student learning. This study aimed to understand how the use of first- or second-hand data affected students' interaction with data within small group and whole-class discussions. The context of this study were middle school chemistry and biology classrooms in which each class completed units working both with first- and second-hand data. Analysis of video and audiotaped class sessions focused on themes relating to: the nature of discussion around measurement, data source, data manipulation, limitations of the data, patterns/inferences, conclusions, use of content knowledge. With the exception of discussions around measurement, which only occurred when students worked with first-hand data, all other themes were present in classroom discussions in varying frequencies regardless of whether the data were first or second-hand. When students engaged with first-hand data they more often engaged in discussions regarding the collection, source, and limitations of the data. In contrast, when students engaged with second-hand data, they often manipulated the data, identified new data patterns, drew conclusions from the data, and considered content knowledge. These results suggest that students meaningfully engage in many science practices around data, but may focus on different features when working with their own or other's data, an important consideration for instructors when planning learning activities.

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[+ Use Real World "Messy" Data]

- Graphing activities that engage students in using contextualized, real-world "messy" data contribute to an understanding of the nature of scientific inquiry and biological systems as well as the development of quantitative reasoning and critical thinking skills.
    - As students typically encounter idealized graph data representing general relationships or trends with little to no variability, students need exposure to and practice working with authentic messy datasets in benefit to their scientific and data literacy.

- To help students, instructors should explicitly discuss potential sources of variability (e.g., sources of error, natural variation) in the graphs used in the classroom and supplemental learning materials.

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[LSE] Kjelvik, M. K., & Schultheis, E. H. (2019). Getting Messy with Authentic Data: Exploring the Potential of Using Data from Scientific Research to Support Student Data Literacy. CBE—Life Sciences Education, 18(2), es2.77(1), 19-29.related information processing, and practice. Theory Into Practice, 1-12. Authentic data from scientific research can be used in the classroom to engage students and develop their cognitive skills in problem-solving and quantitative reasoning (e.g., interpretation, argumentation). In this article, the authors outline five main features of authentic data to characterize the complexity of data-centric learning activities: scope, selection, curation, size, and messiness. Scope of data is determined by the number of variables and information contained within those variables. Data sets narrow in scope can be used to identify specific relationships between variables, whereas, data sets broad in scope may challenge students to select appropriate variables that address the question at hand. Selection of data can range from the instructor providing the exact variables of interest to students independently defining the dataset. Here, opportunities for autonomy in data selection benefits student understanding and ownership in the learning activity. Curation of data or data handling, consists of organizing and preparing the data for visualization, such as transforming raw data (i.e. sums, means, percentages) or merging multiple datasets into one dataset (i.e. datasets with asynchronous collection time frames, missing data points, mismatched scales). The total number of data points that exist in a dataset are defined as the Size and can determine if students can use paper and pen or data software to visualize data in graphs or use data as evidence to support a claim. The last feature of authentic data sets is the Messiness of data (i.e. outliers, missing data points, unexpected trends, variability). Although messy datasets can be frustrating for students, they create learning opportunities to strengthen critical thinking skills and highlight the normalcy of data variability. The authors suggest the five features of authentic data are correlated to some degree and should be instructionally scaffolded over time, starting students with small datasets limited in scope and with clearly defined variables to progressively larger, less-defined, and "messy" data sets. Deliberate practice with authentic data will give students the opportunity to understand the value of data and improve their critical thinking as they collect, analyze, and interpret data.

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[Article] Schultheis, E. H., & Kjelvik, M. K. (2020). Using Messy, Authentic Data to Promote Data Literacy & Reveal the Nature of Science. The American Biology Teacher, 82(7), 439-446. The authors in this article offer advice to K-16 instructors on engaging students with "messy" data (i.e. real-world data that contains variability). This variability arises from natural variation or from the data collection methods itself (e.g., missing values, outliers, unexpected trends). Messy data is a valuable teaching tool in promoting data literacy for future science practitioners as well as the general public because it evokes critical thinking, increases an understanding of the nature of science, and inspires additional research questions. Further, experience with messy data may help students overcome common misconceptions about the quality of data that demonstrates variability, which may result in-part from "smooth" trend lines often depicted in textbooks and other public data displays. Data types can fall into two broad categories: first-hand (collected directly by the students) and second-hand data (from outside sources).

Although students may be limited to the types of phenomena and data they can collect in the classroom setting, first-hand data are important for engaging students and helping them build an understanding of the natural world. Second-hand data may allow students the opportunities to study data collected over long periods of time (e.g., variations in climate), but the lack of data familiarity may lead to the lack of understanding of the variables or the datasets themselves. Therefore, teaching with both first and second-hand data with appropriate practice and scaffolding is vital for providing productive learning experiences. The authors provide a sample sequence of implementation of authentic messy data in the classroom and suggestions on scaffolding data.

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[Article] Kastens, K., Krumhansl, R., & Baker, I. (2015). THINKING BIG: Transitioning your students from working with small, student-collected data sets toward "big data". The Science Teacher, 82(5), 25-31.
Engaging students in inquiry and gathering data to answer questions of interest to them has many advantages, including a greater sense of engagement and ownership as well as a deeper understanding of the data and study system. The increase in publicly available data for use by people outside the community of experts who collected them offers an opportunity for educators to engage students with large, diverse sets of information not easily gathered in a classroom context for studying complex problems. However, engaging students with these datasets has its challenges including their size, larger number of different variables present, and details available in the metadata. Therefore, the approaches students use for data analysis may be insufficient when working with 'big data'. In this pedagogical essay, the authors provide four evidence-based classroom activities to scaffold learning as they transition from working with simple, small student-collected datasets to complex large datasets collected by others: 1) Data puzzles is an activity in which students are given graphs of large datasets to interpret while paying attention to how the data shown relate to biological phenomena. The nested dataset approach allows students to connect with the system under study by (1) collecting their own small dataset, (2) then working with datasets collected by other student groups, and (3) eventually expanding out to examining professionally collected data on the same topic. The predict, observe, explain approach helps to connect students to the data that they will explore (e.g. in a database) by creating a motivating factor to get them to explore more deeply as they evaluate their prediction. Finally, hypothesis arrays can be used when students might not know a lot about the system under study by giving them choices to explore and evaluate using information drawn from the dataset they are examining. These strategies were developed for high school teachers, but are relevant in undergraduate classrooms to provide initial scaffolding before students embark on open inquiry or course-based research experiences over longer periods of engagement and higher student autonomy, for example.

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[Resource] Rosenberg, J., Edwards, A., & Chen, B. (2020). Getting Messy with Data. The Science Teacher, 87(5), 30-34. In this short informative article, the authors provide a summary of free data tools (i.e. Desmos, Google Sheets, JASP, R, and CODAP) and provide implementation strategies on data collection, analysis, and statistical modeling.

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[Resource] Science Education Resource Center (SERC) at Carleton College. The SERC website provides a range of teaching activities intended to strengthen K-16 students' higher-order quantitative reasoning skills. The site currently hosts approximately 400 graphing activities for the lecture and laboratory college classroom across disciplines, including biology (n=~40), environmental science (n=~130), and health sciences (n=5). The posted teaching activities provide lesson outlines (e.g., learning goals, assessment practices) and resources, data sets to engage students with real-world "messy" data (e.g., climate change and plant distribution, water quality), provide math and statistics modules, and explain the use of graphing tools (e.g., how to use Excel to store and present data).

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[+ Utilize Collaborative Work]

- Graphing activities in the classroom can provide collaborative opportunities for students that support their learning and the development of communication and critical-thinking skills.
    - Shared graphing tasks allow students to engage in the cooperative practices of the scientific community by affording opportunities to explain their reasoning and negotiate different viewpoints in making decisions about data.
    - Because there is no one correct way to analyze, display, or interpret data, giving students the opportunity to work together can foster a more creative and reflective process.
    - Collaborative teamwork needs to be supported and managed by instructors. See the 'Group Work' Evidence-Based Teaching Guide for suggestions < link here>.

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[Article] Roth, W. M., & McGinn, M. K. (1997). Graphing: Cognitive ability or practice?. Science Education, 81(1), 91-106. In this review article, the authors advocate for viewing the creation and interpretation of graphs as a competence developed through regular collaborative activities in the field rather than as an innate cognitive ability. Framed by practices experts (e.g., scientists) engage in, the authors describe the use of graphs in three ways: as semiotic objects (collections of signs and symbols representing different aspects of measured variables), rhetorical devices (conveying information to communicate and convince viewers), and conscription devices (a way to invite and engage others into discourse). In all of these roles, creating and making meaning from graphs is contextualized within the community of others who understand the discipline and system under study. Viewing competence with graphing through this lens has classroom implications for the teaching and assessment of students' graphing competence. The authors advocate that students learn the mechanics of graphing (creating the semiotic object), the reason for graphing (rhetorical use), and collective sensemaking with graphing (conscription use) within authentic contexts and the community of practice. Here, students should be encouraged to use graphing not merely as an end point to an activity, but as part of a cycle of collective meaning making with their instructor and peers. From the perspective of assessment, the authors argue that graphing competence is not measured as some universal set of skills, contending that it is less about creating the graph artifact itself or reading off the symbols and trends in a graph, but rather about using graphs to understand the systems under study and in a way that is grounded in the discipline and communities of others familiar with that discipline. Teaching and assessing graphing in this way can not only lead to increased competence with graphing, but can facilitate a broader learning of science.

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[Article] Shofner, M. A., & Marbach-Ad, G. (2017). Group Activity to Enhance Student Collaboration, Graph Interpretation, and Peer Evaluation of Ecological Concepts in a Large-Enrollment Class. Journal of Microbiology & Biology Education, 18(3), 18-3. The authors provide examples of two inquiry-based graphing activities that were implemented in a large-enrollment introductory biology course. Graphing goals for students in this course are to: interpret graphs, compose hypotheses, incorporate biological concepts into their graphs, work in groups, and engage in the peer review process. Prior to the first classroom activity focused on biogeography, students were asked to read about the biology scenario in the textbook and were given a brief introduction in class. Students were divided into small groups and given a worksheet focusing on writing hypotheses related to the biological context and interpreting a graph. To promote collaboration, students were given 15 minutes to work in their small groups with one student assigned to record responses. Afterwards, students were asked to exchange their worksheet with another group and were given 10 minutes to review and comment on another group's answers. Students then received their own worksheets with feedback and asked to review suggestions prior to large group discussion. A similar process was taken with the second activity as students constructed a graph from a data table to explore the relationship between climatic change and population dynamics of a species. Following the first activity, students were asked to reflect on two questions regarding working in a group and the process of peer review. Most students (80%) rated their experience positively with a smaller group (15%) that reported negative feedback attributed to their preference of listening to information in lecture, working by themselves, lack of communication between their team members, and lack of confidence on the biology concepts to provide substantial feedback to others. To ease students into teamwork, the authors recommend assigning each group member a specific task (e.g. recorder, facilitator, presenter).

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[Guide] Group Work . This evidence-based teaching guide provides a rationale for and practical tips for implementing group work in undergraduate biology courses.

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[Resource] Tanner, K., Chatman, L. S., & Allen, D. (2003). Approaches to cell biology teaching: cooperative learning in the science classroom—beyond students working in groups. CBE-Life Sciences Education, 2(1), 1-5. The authors review the features of cooperative learning and contrast it with other types of learning in science classrooms. They present five essential elements of successful implementation of formal cooperative learning in addition to some pedagogical approaches for informal group work.

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[+ Emphasize Intentional Reflection]

- Graph competence involves not only the understanding of graph data, but the ability to critically evaluate the use and effectiveness of graph displays (metarepresentational competence). Instructors can support students' abilities in evaluating graph data by:
    - Providing opportunities for students to regularly reflect upon graphs and graph data.
    - Incorporating activities with structured guidance, in the form of metacognitive questions. This has been found to promote reflection in the decision-making process of college students when constructing and reasoning with graphs. Specifically, reflection prompts can ask students to reflect on their own decision making and understanding when engaged with graphing.
    - Social activities that engage students in critiquing and constructing self-generated graphs benefit the development of graphing skills as well as one's conceptual understanding of scientific events.

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[Article] diSessa AA (2004) Metarepresentation: native competence and targets for instruction. Cognition and Instruction 22: 293-331. This review article aims to describe the difference between representational competence (RC, one's ability to produce and use a variety of standard representations) and metarepresentational competence (MRC, one's critical, reflective and inventive strategies that can be applied to any representation). MRC entails five key principles: (1) inventing or designing new representations, (2) critiquing and comparing the adequacy of representations and judging their suitability for different tasks, (3) understanding the purposes of representations, generally, and in particular contexts and how they are useful, (4) explaining representations, and (5) learning new representations with ease. The MRC perspective acknowledges that there is no singular 'best' representation for a given set of data, but rather that a number of existing and new representations could be appropriate for a given context and purpose, but that each has affordances and limitations that need to be explored. The author provides an overview of the vast representational competence literature and how that has shaped the knowledge base that has informed instruction. The author then describes, with examples from the literature, how the lens of MRC can provide further insight into the development of student competence with representations and an acknowledgment of intrinsic ability that students possess which is a resource for further learning. The strict adherence to norms and a singular 'best' solution for a representation is challenged and the author highlights the importance of an exploration and critique of multiple representations.

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[Article] Angra, A. & Gardner S.M. (2016).Development of a Framework for Graph Choice and Construction. Advances in Physiology Education 40: 123–128. The ability to create and make use of visual representations to solve problems is known as representational competence. In the context of graphing in biology this requires a knowledge of different graph types, data types, and features of the biological system from which the data arose. Metarepresentational competence (MRC) extends from this and incorporates reflection as an important component for successful construction and reasoning with graphs and other external representations. In graphing, reflection reveals students' own awareness of their understanding of graphs and gaps in their knowledge. In this paper, the authors present two validated learning and instructional graphing tools, a Step-by-Step Guide and Guide to Data Displays that can be used to teach students to reflect on their decision-making processes. The Step-by-Step Guide is divided into three phases, with the last phase being a five-step reflection phase that prompts the student to: (1) check the alignment of their graph to the research question and hypothesis; (2) provide the advantages of the representation; (3) provide the disadvantages; (4) the take-home message; and (5) other ways to represent data. The Guide to Data Displays organizes the common types of visual representation (graph and tabular data) used in biology as well as their respective advantages and disadvantages in a table. Provided in the supplemental materials is a blank Guide to Data Displays which can be used as a tool to help students of varying experiences reflect on graphs throughout the semester.

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[Article] McFarland, J. (2010). Teaching and assessing graphing using active learning. MathAMATYC Educator, 1(2), 32-39. In this article, the author identifies three common challenges to graph learning in the college classroom as well as instructional approaches to overcome these potential challenges. The three challenges were: 1) generating student interest in effective graphing practices (e.g., selecting data appropriate graph types), 2) encouraging students to critique graphs in their textbooks and the popular media, and 3) the student assumption that using graphing software will automatically produce appropriate graphs for a given data set. To overcome these challenges, the author uses the principles of active learning to share a 90-minute activity that requires biology undergraduates enrolled in a laboratory (or lecture) course to collaboratively practice cognitive and metacognitive skills to improve graphing skills. After an introduction on graphs, students are divided into small groups and asked to hand draw a graph from a provided data set, and reflect on their decision-making through a series of questions around the purpose of graphs, criteria for appropriate graph construction, and alternative graph types. After graph construction, students are engaged in a class discussion about the importance of graphs and published examples generated by other professionals and scientists. Finally, each group shares their graph, observations about the data trends, and questions evoked by the graph. To translate this activity to long-term student learning, students are required to complete two graph self-assessment questions on graph choice and quality, which they must submit along with their lab report. End of the semester feedback from students on the graphing activity and subsequent reflections reveal the impact of multiple practice and reflections rounds.

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[Article] Matuk, C., Zhang, J., Uk, I., & Linn, M. C. (2019). Qualitative graphing in an authentic inquiry context: How construction and critique help middle school students to reason about cancer. Journal of Research in Science Teaching, 56(7), 905-936. This study investigated how the incorporation of a qualitative, social practice-approach to graphing in scientific inquiry impacts pre-college biology students' understanding of both graphs and science. A qualitative approach to graphing is described by the authors to differ from a quantitative approach by focusing on the identification of general data patterns and trends rather than pointwise details (i.e. the plotting and interpretation of specific data points). In the two-part study, data were collected from middle school students (n= 147) before and after a socially-contextualized multi-week unit on cell division and cancer to assess the value of integrated qualitative graphing activities. For each study, the authors analyzed pre- and post-test assessments designed to measure learning gains on key concepts and targeted graphing skills (i.e. critique, construction) using standardized rubrics. The results demonstrate that the incorporation of qualitative graphs in instruction benefited students' conceptual understanding as well as developed competency in using graphs as narrative tools to express this understanding. In addition, the authors reported on how the actions of critiquing and constructing qualitative graphs distinctly benefited students in unique ways that improved their ability to integrate their knowledge of science and graphs. Specifically, critiquing graphs helped students improve their scientific explanations within the unit, while constructing graphs led students to link key science ideas within both their in-unit and post-unit explanations. The authors conclude that the inclusion of qualitative graphs into inquiry-based activities can simultaneously strengthen students' graphing competencies and conceptual understanding. Design considerations for critique and construction activities are discussed in the context of extant learning science and science education literature.

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[Resource] Tanner, K. D. (2012). Promoting student metacognition. CBE—Life Sciences Education, 11(2), 113-120. This resource is an essay that translates metacognition research into practical recommendations for instructors. The essay provides actionable advice that instructors can follow to promote metacognition in their students as well as in themselves.

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[Guide] Student Metacognition . Graphing is a social practice of science in which the community of scientists question each other and jointly make meaning together from graphs. This evidence-based teaching guide reviews seminal literature on the benefits of and practical tips for supporting student metacognition. In particular, the authors provide a section on social metacognition in which students support each other's metacognition through the sharing of their own metacognition and reasoning and questioning and supporting each other. The role of instructors in promoting and scaffolding social metacognition are reviewed.

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Designs in Action

This section of the guide presents published examples of how graphing is taught in the biology lecture or in an experiential setting. As modeled in the examples, instructors can introduce and integrate graphing into the classroom by:

- Incorporating graphing activities into lecture and laboratory settings with intentional, often minor, modifications to existing curriculum that contribute to the development of graph competence.
    - Allot time to model expert thinking in graph reading, interpreting, drawing, and evaluation to assist students in understanding graphing norms and practices
    - Provide regular opportunities for students to thoughtfully engage in graphing practices, including reflection and iteration.
    - Employ assessments and reflective activities that help identify gaps in student knowledge and improve future interactions with graph data inside and outside of the classroom.

    - To support the learning of how to prepare effective figures, ask student to: (a) find a few examples of published figures that include the same experimental data as their project, (b) assess the published figure on its components and effectiveness, and (c) create their own checklist from the figure which they used when preparing their own figure.
- Using materials from free online websites provide learning objectives, short graphing exercises and assessments that can be easily incorporated into the curriculum. <link to instructor checklist>
- Engaging students in the collection, curation, and/or analysis of real-world, messy, meaningful data to enhance psychological features relevant to graphing (self-confidence, motivation) and critical thinking skills by connecting scientific inquiry and graph practices .

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[Article] **Taylor, M. F. (2010). Making Biology Teaching More "Graphic". The American Biology Teacher, 72(9), 568-571.** In this short "how-to" essay, the author describes the step-wise general classroom approach taken to introduce the concept of variables and correlations as they pertain to relational line graphs. A hypothetical experiment with data on investigating the effect of light intensity on plant growth rate is presented and can be used as an example when teaching students how to create a graph and interpret the take-home message. The essay also provides advice on how to teach college students about positive and negative correlations and upon mastery, how to transfer this knowledge to positive and negative feedback loops. An example is provided on how to graphically teach negative feedback control as students are asked to predict how the duration of exercise affects a person's blood glucose. In a sample discussion, the author explains how to help students think in terms of variables through multiple graph displays representing data relationships (e.g., insulin levels in response to glucose absorption) relevant to the situating problem. Although the context of this manuscript is largely focused on physiology, the author recommends teaching relational graphing in ecology (e.g. understand the effect of nutrient runoff up the food chain in a lake) or any sub-discipline where students have to make sense of large number of variables and how each variable impacts other variables.

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[LSE] Bray Speth E., Momsen, J.L., Moyerbrailean, G.A., Ebert-May, D., Long, T.M., Wyse, S.A. & Linton, D. (2010). 1, 2, 3, 4: Infusing quantitative literacy into introductory biology. CBE-Life Sciences Education 9: 323-332. This article explores how a team of instructors infused quantitative concepts within the existing framework (course content and learning objectives) of a large-scale introductory biology course to develop students' quantitative literacy (QL) skills. Using a learner-centered instructional approach, students participated in quantitative thinking with biological scenarios throughout the term including: iterative assessments to test QL skills were regularly designed and administered as part of normal course activities (e.g., in-class work, homework, quizzes) allowing instruction to be tailored to the students' needs and abilities. Pre- and post-semester performance tasks grounded in problems drawn from real-world biological research were used to evaluate students' ability to represent data graphically and articulate data-driven arguments. Baseline data indicated introductory students had difficulties upon entering the class with representing data on a graph, properly labeling the graph axes, and formulating complete and correct data-based claims with appropriate reasoning – which the authors argue lends further evidence to the need for practice of quantitative skills in college science. Comparative analysis of the pre/post assessments found that students made significant gains in their ability to graphically represent numerical data during the course. The authors conclude that it is feasible to incorporate QL concepts in the context of an existing course to help students develop quantitative skills, and offer recommendations to other instructors on how to infuse the learning of quantitative skills into their courses. The article's method section includes the performance tasks and associated rubrics as well as employed teaching modules that can be adopted or used as examples to construct quantitatively based teaching activities or assessments.

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[Article] **Picone, C., Rhode, J., Hyatt, L., & Parshall, T. (2007). Assessing gains in undergraduate students' abilities to analyze graphical data. Teaching Issues and Experiments in Ecology, 5(July), 1-54**. This study examined the impact of activities designed and integrated into introductory ecology and environmental science courses on students' data analysis and graphing abilities at four institutions. Teaching activities to train students how to interpret ecological data were developed to engage students in collaborative, active learning practices and incorporated several evidence-based strategies for teaching data skills, including: the "Step-One, Step-Two" approach of graph interpretation, requiring graphs to be sketched by hand prior to plotting data using visualization software, and introducing course content through data-driven exercises focused on real-world scientific problems. Students (n=240) completed assessments at the onset, during, and end of the term developed by the authors to measure whether the activities in the courses improved participants' abilities to create and interpret graphs. Differences in pre-post test data indicated student gains in the interpretation of simple bar graphs and scatterplots as well as their ability to construct graphs from raw data. Persisting graphing difficulties were also documented via the performance measures as students showed smaller gains in their skills in identifying independent and dependent variables, detecting trends in data with variation, and interpreting interactions among variables in complex graphs which the authors then identify as challenges for instructors to focus on in the development of analytical skills. The article includes an unvalidated scenario-based assessment tool designed for the study that could be adopted by instructors interested in measuring their students' graphing and data reasoning skills as well as an example handout to guide students in graph reading and interpretation.

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[Article] **Weigel, E., and Angra, A. (accepted) Teaching in Tandem: Using graphs in an active-learning classroom to shape students' understanding of biology concepts. Journal of College Science Teaching.** The goal in this study was to understand how explicit instruction on graphing and usage of published graphing materials affected students' knowledge of various graph types and interpretation skills over the course of the semester in an upper-level animal behavior lecture course for biology majors. Each lecture began with an animal behavior scenario and students (n=41) were asked to: identify a research question and hypothesis, sketch their prediction in a graph, compare their sketch with the graph from literature, reflect on the findings and how they contribute to animal behavior. Individual and think-pair-share activities were discussed at each step to give students real-time feedback on their skills. Students' graphing abilities were formally evaluated across three exams on open-ended questions. Improvement over the semester was observed, particularly in interpreting the purpose of the graph, the nature of the data, the relationships between independent and dependent variables and the take-home message. Responses to a 12-question pre-post survey containing open-ended and multiple choice questions revealed student improvement in recalling the different parts of a graph resulting from the use of a graphing rubric and peer assessment. However, in using a graph rubric, students gave more directed feedback on graph mechanics and graph communication, straying away from the graph choice elements in the graph rubric. The use of published graphing materials together with explicit instruction and repeated practice was helpful in supporting students to improve their graphing knowledge and identified potential targets for guidance and instruction.

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[Article] Crowther, G. J. (2017). Which way do the ions go? A graph-drawing exercise for understanding electrochemical gradients. Advances in Physiology Education, 41: 556–559. In this short illuminations essay, the author presents a five-step graph-drawing method as a way to help his introductory biology students solve problems with electrochemical driving forces. Specifically, the five-step process allows students to determine the membrane potential, the specificity of the ion's potential to flow inwards or outwards, and whether the cell will depolarize or hyperpolarize. Although this process is less mathematical and graphically simple (no axes scale), it helps the student quickly visualize the process. This is an example of how instructors can encourage higher-order thinking with the biology content while allowing them a new way to graphically visualize biological phenomena in a lecture classroom.

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[Article] Harsh J.A. and Schmitt-Harsh M.L. (2016) Instructional Strategies to Develop Graphing Skills in the College Science Classroom. The American Biology Teacher 78(1): 49-56. This article explores the design and implementation of a short-term intervention to hone college science students' graphing skills. The authors developed an inquiry-based ecology unit for introductory, non-science students that emphasized graphing theory and practice as part of studying a real-world problem (i.e. the water quality of a campus stream). Five key instructional design features for teaching graphing drawn from the literature were incorporated into the unit for the deliberate practice of graph construction and interpretation: (1) engaging students in authentic scientific inquiry through the investigation of realistic and contextualized problems, (2) exposing students to "messy" or complex data sets, (3) a two-step data analysis approach that first engages students' cognitive processes and then uses technology for visualization purposes, (4) explicit graphing instruction that includes instructor modeling, and (5) collaborative practices to make sense of and communicate data. Students improved significantly from a pre- to a post assessment consisting of graphing construction and interpretation questions which were informed from pre existing validated instruments. Likewise, in a supplemental questionnaire, students self-reported lower levels of anxiety and frustration when presented graph data upon completion of the unit. Student feedback highlighted the perceived positive impact of the unit on their graphing skills as well as identified the instructional design features that they felt most contributed to their learning, with a high rating for: personal data collection, working in a group, understanding each group's role in the overall class data, and using graphing software. The authors conclude the article with suggestions for implementation adaptations to meet the needs of course- and lab-based activities across disciplines to help advance secondary and college students' graphing skills.

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[Article] **Kirby, C. K., Fleming-Davies, A., & White, P. J. (2019). The Figure of the Day: A Classroom Activity to Improve Students' Figure Creation Skills in Biology. The American Biology Teacher, 81(5), 317-325.** This article examines the effects of a scaffolded graph interpretation learning activity on college students' graph generation skills. The authors share an inquiry-style, puzzle-like figure analysis activity called "Figure of the Day" (FotD) which was implemented once a week for six weeks in an introductory organismal biology laboratory using data displays not related to the field or course content. In the treatment condition, students were asked to interpret a figure with one or several elements of contextual information missing (e.g., titles, captions, axes labels, axes units, legend text, and labels within figures), while the control condition of FotD did not contain any missing contextual information. In the treatment activity, students were asked to, individually and then collaboratively, observe the figure and brainstorm ideas about the variables displayed and possible explanations to the colors or symbols present. This was followed by a class debriefing, in which the instructor displayed the original published figure with all of the contextual information and led a discussion on the ideas that the figure authors were trying to communicate. A similar approach was taken with the control FoTD activities, however, students in the control group did not brainstorm ideas about missing information. To measure the impact of the FotD on students' figure creation skills, students were asked to construct a graph pre- and post- FotD in a series of prompts. Student graphs were scored using a seven- category rubric, which revealed significant gains in both the treatment and control FoTD groups in the post-assessment. When asked to provide feedback on the positive and negative aspects of the FotD, students in the treatment group enjoyed the activity more. However, students in the control treatment reported a higher perceived impact of the FotD on their figure interpretation and creation skills. This suggests that regular interaction with figures in the style of the FotD activity can improve all students' figure creation skills in a meaningful and enjoyable way.

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[Article] **Violin, C. R., & Forster, B. M. (2019). An Introductory Module and Experiments To Improve the Graphing Skills of Non-Science Majors. Journal of Microbiology & Biology Education, 20(3).** In this article, the authors share a three-part graphing module created for non-science undergraduate students enrolled in a laboratory course. The three-part scaffolded activity consists of the lecture, the class activity, and a group activity which is followed by a discussion on experimental design, variables, data types and data collection methods. For graph construction, graph choice is discussed as well as the appropriate mechanics needed to construct an informative graph. For graph interpretation, students are instructed on correlations, linear and non-linear trends, interpolating and extrapolating data. Students are also provided a two-sentence framework on how to convey the graph interpretation. Students practice graphing data in Microsoft Excel with guided instruction on computing regression models. Students work in small groups, collect their own data, and practice graphing four times over the semester. The authors state anecdotally that frequent graphing assignments have improved graphing skills in non-majors.

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[Article] **Hammett, A., & Dorsey, C. (2020). Messy Data, Real Science. The Science Teacher, 87(8).** In this article, the authors present a real-world data experience for students in the context of harmful algal blooms (HABs), which poses danger to humans and other animal life. Given the relevance to students' everyday lives (water quality) and that there is still not a clear answer as to why HABs occur, the topic is well-fit for supporting an authentic and meaningful investigation for learners of various backgrounds. The authors outline design considerations drawn from the literature for effectively engaging students in data-rich investigations (i.e. making it interesting, embracing a systems view, being mindful of data complexity, and scaffolding data learning activities) and their respective instructional enactment. In their paper, the authors explain how they engaged students in authentic data experience in two ways. First, students are asked to collect and process data from their local water reservoirs using various instruments, students can measure a variety of variables (e.g. turbidity, pH, dissolved oxygen, phytoplankton). By processing and analyzing their own data first, students have more contextual familiarity with the larger, messier data sets that are collected from scientists doing HAB research. Second, students are exposed to "big data" sets to ensure authentic data exploration with enough data points and parameters for data analysis, visualization, and understanding the relationship between variables. Finding the right sized data set, with appropriate scope and messiness are important considerations to make when engaging students in data that they have not collected themselves.--

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[Article] Gray, C. E., & Contreras-Shannon, V. E. (2017). Using Models From the Literature and Iterative Feedback to Teach Students to Construct Effective Data Figures for Poster Presentations. Journal of College Science Teaching, 46(3), 74. The purpose of this study was to test a pedagogical method to teach students how to generate effective data representations in a sophomore-level Cell and Molecular Methods course-based research experience (CURE). There were two course instructors who each taught a control and a treatment section. Comparisons were drawn between figures prepared for posters by students who were (treatment group) and were not (control group) part of the intervention designed to develop and practice skills in representing authentic, messy data. To prepare effective figures, students in the treatment group were asked to: (a) find a few examples of published figures that included the same experimental data as their project, (b) assess the published figure on its components and effectiveness, and (c) create their own checklist from the figure which they used when preparing their own figure. The instructor then provided detailed feedback on the figure generated by the students, who then revised their figure. Towards the end of the semester, students collaborated with one or two classmates to pool their knowledge in designing their final figures for the poster. A general rubric was created to score 34 figures (17 figures form the control group and 17 from the experimental group) from the final poster presentations. Across all rubric categories, students who were engaged in the pedagogy sections received the highest scores. The authors conclude with excerpts from students on the usefulness of iterative feedback. Although it may take more time to provide iterative feedback to students, the authors state that it is an excellent opportunity for the student and instructor to engage in real-world tasks of understanding and visualizing data.

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[Article] Angra, A., Dalgleish, H. J., Chambers, S. M., Pita, D., & Emery, N. C. (2020). Data, distributions, and hypotheses: Exploring diversity and disturbance in the tallgrass prairie. CourseSource. In the context of ecological disturbance and how it shapes a tallgrass prairie ecosystem, the authors present a four-week lab module designed for an ecology laboratory course. Over the course of the module, students engage in authentic science practices consisting of: reading primary literature, working in teams to write hypotheses, designing experiments, collecting species composition data from a local tallgrass prairie ecosystem and comparing portions that were burned in different seasons, and presenting findings in graphs. At each step, students complete writing assignments and receive feedback. The module concludes by giving students real-world scenarios and asking them to form management decisions that integrate content from their prairie study with the constraints in their scenario. Students then present and defend their proposed solution to the class. All course materials (readings, pre-lab quizzes, writing and graphing assignments, etc.) for instructors and students can be accessed through the CourseSource website.

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[Resource] A project of BioQUEST, the Quantitative Undergraduate Biology Education and Synthesis (QUBES) platform provides an open community space for life science educators to advance transformative STEM education efforts. The website hosts open-access classroom activities and CourseSource, a peer-reviewed journal of teaching resources, as well as faculty mentoring networks and educator communities on varying topics. Of relevance here, a range of resources pertaining to graph instruction are available from this platform.

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