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The role of introductory geoscience courses in preparing teachers—and all students—for the future: Are we making the grade? SUPPLEMENTAL DATA

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TABLE S1. EARTH AND SPACE SCIENCE PERFORMANCE EXPECTATIONS*

Middle school	**High school**
Earth's Place in the Universe*	
Develop and use a model of the Earth-sun-moon system to describe the cyclic patterns of lunar phases, eclipses of the sun and moon, and seasons. Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system. Analyze and interpret data to determine scale properties of objects in the solar system.	Use mathematical or computational representations to predict the motion of orbiting objects in the solar system.
Construct a scientific explanation based on evidence from rock strata for how the geologic time scale is used to organize Earth's 4.6-billion-year-old history.	Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history.
Earth's Systems	
Develop a model to describe the cycling of Earth's materials and the flow of energy that drives this process.	Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.
Construct an explanation based on evidence for how geoscience processes have changed Earth's surface at varying time and spatial scales.	Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.
Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.	Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.
Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.	Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes.
Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.	Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.
Collect data to provide evidence for how the motions and complex interactions of air masses results in changes in weather conditions.	
	Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth.
Earth and Human Activity	
Construct a scientific explanation based on evidence for how the uneven distributions of Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes. Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects.	Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity.
	Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.
Construct an argument supported by evidence for how increases in human population and per-capita consumption of natural resources impact Earth's systems.	Create a computational simulation to illustrate the relationships among management of natural resources, the sustainability of human populations, and biodiversity. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.
Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.	Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
Ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century.	Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.

* *from* NGSS Lead States, 2013, Next Generation Science Standards: For States, By States, Washington, D.C., The National Academies Press, 324 p.

Table S2. Science and Engineering Practices (SEPs) for Middle and High School

SEP1: Asking questions and defining problems

High school

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information
- Ask questions that arise from examining models or a theory, to clarify and/or seek additional information and relationships.
- Ask questions to determine relationships, including quantitative relationships, between independent and dependent variables
- Ask questions to clarify and refine a model, an explanation, or an engineering problem
- Evaluate a question to determine if it is testable and relevant
- Ask questions that can be investigated within the scope of the school laboratory, research facilities, or field (e.g., outdoor environment) with available resources and, when appropriate, frame a hypothesis based on a model or theory.
- Ask and/or evaluate questions that challenge the premise(s) of an argument, the interpretation of a data set, or the suitability of a design.
- Define a design problem that involves the development of a process or system with interacting components and criteria and constraints that may include social, technical, and/or environmental considerations

Middle school

- Ask questions that arise from careful observation of phenomena, models, or unexpected results, to clarify and/or seek additional information.
- Ask questions to identify and/or clarify evidence and/or the premise(s) of an argument.
- Ask questions to determine relationships between independent and dependent variables and relationships in models.
- Ask questions to clarify and/or refine a model, an explanation, or an engineering problem.
- Ask questions that require sufficient and appropriate empirical evidence to answer.
- Ask questions that can be investigated within the scope of the classroom, outdoor environment, and museums and other public facilities with available resources and, when appropriate, frame a hypothesis based on observations and scientific principles.
- Ask questions that challenge the premise(s) of an argument or the interpretation of a data set.
- Define a design problem that can be solved through the development of an object, tool, process or system and includes multiple criteria and constraints, including scientific knowledge that may limit possible solutions.

SEP2: Developing and using models

High school

- Evaluate merits and limitations of two different models of the same proposed tool, process, mechanism or system in order to select or revise a model that best fits the evidence or design criteria.
- Design a test of a model to ascertain its reliability.
- Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system
- Develop and/or use multiple types of models to provide mechanistic accounts and/or predict phenomena, and move flexibly between model types based on merits and limitations
- Develop a complex model that allows for manipulation and testing of a proposed process or system.
- Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems.
- Use a model to provide mechanistic accounts of phenomena.

Middle school

- Evaluate limitations of a model for a proposed object or tool.
- Develop or modify a model (based on evidence) to match what happens if a variable or component of a system is changed.
- Use and/or develop a model of simple systems with uncertain and less predictable factors.
- Develop and/or revise a model to show the relationships among variables, including those that are not observable but predict observable phenomena.
- Develop and/or use a model to predict and/or describe phenomena.
- Develop a model to describe unobservable mechanisms.
- Develop and/or use a model to generate data to test ideas about phenomena in natural or designed systems, including those representing inputs and outputs, and those at unobservable scales.

SEP3: Planning and carrying out investigations

High school

- Plan an investigation or test a design individually and collaboratively to produce data to serve as the basis for evidence as part of building and revising models, supporting explanations for phenomena, or testing solutions to problems. Consider possible confounding variables or effects and evaluate the investigation's design to ensure variables are controlled.
- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Plan and conduct an investigation or test a design solution in a safe and ethical manner including considerations of environmental, social, and personal impacts.
- Select appropriate tools to collect, record, analyze, and evaluate data.
- Make directional hypotheses that specify what happens to a dependent variable when an independent variable is manipulated.
- Manipulate variables and collect data about a complex model of a proposed process or system to identify failure points or improve performance relative to criteria for success or other variables.

Middle school

- Plan an investigation individually and collaboratively, and in the design: identify independent and dependent variables and controls, what tools are needed to do the gathering, how measurements will be recorded, and how many data are needed to support a claim.
- Conduct an investigation and/or evaluate and/or revise the experimental design to produce data to serve as the basis for evidence that meet the goals of the investigation.
- Evaluate the accuracy of various methods for collecting data.
- Collect data to produce data to serve as the basis for evidence to answer scientific questions or test design solutions under a range of conditions.
- Collect data about the performance of a proposed object, tool, process or system under a range of conditions.

SEP4: Analyzing and interpreting data

High school

- Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims or determine an optimal design solution.
- Apply concepts of statistics and probability (including determining function fits to data, slope, intercept, and correlation coefficient for linear fits) to scientific and engineering questions and problems, using digital tools when feasible.
- Consider limitations of data analysis (e.g., measurement error, sample selection) when analyzing and interpreting data
- Compare and contrast various types of data sets (e.g., self-generated, archival) to examine consistency of measurements and observations.
- Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.

- Analyze data to identify design features or characteristics of the components of a proposed process or system to optimize it relative to criteria for success.

Middle school

- Construct, analyze, and/or interpret graphical displays of data and/or large data sets to identify linear and nonlinear relationships.
- Use graphical displays (e.g., maps, charts, graphs, and/or tables) of large data sets to identify temporal and spatial relationships.
- Distinguish between causal and correlational relationships in data.
- Analyze and interpret data to provide evidence for phenomena.
- Apply concepts of statistics and probability (including mean, median, mode, and variability) to analyze and characterize data, using digital tools when feasible.
- Consider limitations of data analysis (e.g., measurement error), and/or seek to improve precision and accuracy of data with better technological tools and methods (e.g., multiple trials).
- Analyze and interpret data to determine similarities and differences in findings.
- Analyze data to define an optimal operational range for a proposed object, tool, process or system that best meets criteria for success.

SEP 5: Using Mathematics and Computational Thinking

High school

- Create and/or revise a computational model or simulation of a phenomenon, designed device, process, or system.
- Use mathematical, computational, and/or algorithmic representations of phenomena or design solutions to describe and/or support claims and/or explanations.
- Apply techniques of algebra and functions to represent and solve scientific and engineering problems.
- Use simple limit cases to test mathematical expressions, computer programs, algorithms, or simulations of a process or system to see if a model “makes sense” by comparing the outcomes with what is known about the real world.
- Apply ratios, rates, percentages, and unit conversions in the context of complicated measurement problems involving quantities with derived or compound units (such as mg/mL, kg/m^3, acre-feet, etc.).
- Decide if qualitative or quantitative data are best to determine whether a proposed object or tool meets criteria for success.

Middle school

- Use digital tools (e.g., computers) to analyze very large data sets for patterns and trends.
- Use mathematical representations to describe and/or support scientific conclusions and design solutions
- Create algorithms (a series of ordered steps) to solve a problem.
- Apply mathematical concepts and/or processes (e.g., ratio, rate, percent, basic operations, simple algebra) to scientific and engineering questions and problems.
- Use digital tools and/or mathematical concepts and arguments to test and compare proposed solutions to an engineering design problem.

SEP 6: Constructing Explanations & Designing Solutions

High school

- Make a quantitative and/or qualitative claim regarding the relationship between dependent and independent variables.
- Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources (including students’ own investigations, models, theories, simulations, peer review) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects.
- Apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.
- Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.

Middle school

- Construct an explanation that includes qualitative or quantitative relationships between variables that predict(s) and/or describe(s) phenomena.
- Construct an explanation using models or representations.
- Construct a scientific explanation based on valid and reliable evidence obtained from sources (including the students' own experiments) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.
- Apply scientific ideas, principles, and/or evidence to construct, revise and/or use an explanation for real- world phenomena, examples, or events.
- Apply scientific reasoning to show why the data or evidence is adequate for the explanation or conclusion
- Apply scientific ideas or principles to design, construct, and/or test a design of an object, tool, process or system.
- Undertake a design project, engaging in the design cycle, to construct and/or implement a solution that meets specific design criteria and constraints
- Optimize performance of a design by prioritizing criteria, making tradeoffs, testing, revising, and re- testing.

SEP 7: Engaging in Argument from Evidence

High school

- Compare and evaluate competing arguments or design solutions in light of currently accepted explanations, new evidence, limitations (e.g., trade-offs), constraints, and ethical issues
- Evaluate the claims, evidence, and/or reasoning behind currently accepted explanations or solutions to determine the merits of arguments.
- Respectfully provide and/or receive critiques on scientific arguments by probing reasoning and evidence, challenging ideas and conclusions, responding thoughtfully to diverse perspectives, and determining additional information required to resolve contradictions.
- Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.
- Make and defend a claim based on evidence about the natural world or the effectiveness of a design solution that reflects scientific knowledge and student-generated evidence.
- Evaluate competing design solutions to a real-world problem based on scientific ideas and principles, empirical evidence, and/or logical arguments regarding relevant factors (e.g. economic, societal, environmental, ethical considerations).

Middle school

- Compare and critique two arguments on the same topic and analyze whether they emphasize similar or different evidence and/or interpretations of facts.
- Respectfully provide and receive critiques about one's explanations, procedures, models, and questions by citing relevant evidence and posing and responding to questions that elicit pertinent elaboration and detail.
- Construct, use, and/or present an oral and written argument supported by empirical evidence and scientific reasoning to support or refute an explanation or a model for a phenomenon or a solution to a problem.
- Make an oral or written argument that supports or refutes the advertised performance of a device, process, or system based on empirical evidence concerning whether or not the technology meets relevant criteria and constraints.
- Evaluate competing design solutions based on jointly developed and agreed-upon design criteria.

SEP 8: Obtaining, Evaluating, Communicating Information

High school

- Critically read scientific literature adapted for classroom use to determine the central ideas or conclusions and/or to obtain scientific and/or technical information to summarize complex evidence, concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.
- Compare, integrate and evaluate sources of information presented in different media or formats (e.g., visually, quantitatively) as well as in words in order to address a scientific question or solve a problem.
- Gather, read, and evaluate scientific and/or technical information from multiple authoritative sources, assessing the evidence and usefulness of each source.
- Evaluate the validity and reliability of and/or synthesize multiple claims, methods, and/or designs that appear in scientific and technical texts or media reports, verifying the data when possible.
- Communicate scientific and/or technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (i.e., orally, graphically, textually, mathematically).

Middle school

- Critically read scientific texts adapted for classroom use to determine the central ideas and/or obtain scientific and/or technical information to describe patterns in and/or evidence about the natural and designed world(s).
- Integrate qualitative and/or quantitative scientific and/or technical information in written text with that contained in media and visual displays to clarify claims and findings.
- Gather, read, and synthesize information from multiple appropriate sources and assess the credibility, accuracy, and possible bias of each publication and methods used, and describe how they are supported or not supported by evidence.
- Evaluate data, hypotheses, and/or conclusions in scientific and technical texts in light of competing information or accounts.
- Communicate scientific and/or technical information (e.g. about a proposed object, tool, process, system) in writing and/or through oral presentations.

METHODS

Survey analysis

The National Geoscience Faculty Survey has been administered four times. A complete description of the survey background, administration process, and the question items is provided on the web (https://serc.carleton.edu/NAGTWorkshops/baseline_survey/survey_background). Some questions have appeared in all four administrations, while others have been added, removed, and/or rephrased. The subset of questions selected for analysis here include some that have been administered once, twice, and four times.

In each year of the survey, after responding to a set of demographic questions, respondents were asked questions about the nature of their teaching in the previous academic year. The answers to these questions served as a branch point in the survey that directed respondents to answer further questions about their teaching in either an introductory or majors course or sent them to the last section of the survey if they did not do any teaching. The analyses here include only those who completed questions about introductory courses (n = 813 in 2004, n = 994 in 2009, n = 972 in 2012, and n = 1074 in 2016), which were extracted from the complete set of responses for each survey administration (Table S2).

In the section of the survey for introductory courses, respondents answered several questions (fourteen in the 2016 survey), most of which had several components. Response frequencies were analyzed for questions with yes-no and other single response options. Free-entry questions required recoding prior to analysis; relevant free-entry questions included institution name, the name of the course (about which they would answer the remainder of the survey questions), and the number of students in that same course. Institution names were recoded for institution type (Carnegie classification). Entries for the number of students were summed for each year, and individual entries were also categorized into small (≤ 30), medium (31-80), and large (>80).

Course names were analyzed in three stages. First, course titles that differed only by capitalization (physical geology vs. Physical Geology), misspelling (physcal geology), or abbreviations (Intro to physical geology vs. Introduction to physical geology) were grouped together and considered to be the same title. Subsequently, course titles that appeared to address similar subject areas were combined (e.g. physical geology, introduction to geology, the solid Earth). Finally, similar subject areas (e.g. atmospheric science, meteorology, weather) were combined into broader disciplinary areas (e.g. atmosphere).

Analyses of relevant questions were broken down by survey year, institution type, discipline of the course, size of the course, nature of students in the course, or a combination. Statistical analyses were conducted using the software package IBM SPSS Statistics version 24.

Syllabus analysis

Syllabi were uploaded to SERC by participants in *On the Cutting Edge* workshops offered since 2002 as a requirement prior to the beginning of the workshop. All participants who participated in workshops where syllabi were requested would have received an invitation to participate in the survey as well, though it may not have reached them if they had changed institutions or email addresses.

To obtain syllabi for analysis, I searched for introductory course descriptions (webpages) in the SERC database, excluding (1) course descriptions without a downloadable document that represented the information presented to students, (2) syllabi for courses that had not yet been taught (if this was stated in the course description), and (3) syllabi for courses that had any prerequisites other than basic skills (many courses in historical geology, for example, although described as introductory, require physical geology as a prerequisite). I downloaded syllabi that met my criteria (n = 152) and recorded information into a spreadsheet, including the year of the course, the institution where it was taught, the course title, type (lecture, lab, integrated, online), topics, learning outcomes, and evaluation/assessment data.

Course titles were grouped using the same method as the survey data. Institution data were recoded to institution type to match how they were coded in the survey. Because survey questions asked respondents to describe the “lecture portion” of their course, only syllabi for courses described as lecture, integrated lecture and lab, or online were included in subsequent analyses.

Lecture topics were recorded as they were presented in the course schedule and grouped in a similar fashion as the course titles. The number of topics listed separately were counted and recorded along with the number of weeks of the course. If present, learning outcomes were recorded and action verbs were categorized according to Bloom’s revised taxonomy (Krathwohl, 2002), counted, and compared with the action verbs in the performance expectations at the middle and high school levels (Table S1). Any non-cognitive action verbs, particularly those that addressed the affective domain, such as *appreciate*, were not included in the count. Most syllabi included information about how students would be evaluated, including the relative contributions of several different kinds of assessments. I recorded assessment types and their contributions, normalizing all point distributions to 100%. In order to categorize assessments, I used the exact language in the syllabus whenever possible, resulting in the following categories: homework (indicated in the syllabus by “homework” or “assignments”), in-class activities (including “clicker questions”), labs, attendance, participation, projects/reports (including final projects, presentations, field trip reports), quizzes, exams, and final exam.

TABLE S3. SURVEY RESPONDENTS

Survey year	Requests	Responses	Response rate	Presented intro section	Completed intro section
2004	5700	2207	39%	852	**813**[†]
2009	5917	2874	49%	1041	**994**[§]
2012	7813	2466	32%	1007	**972**[§]
2016	9596*	2615	27%	1096	**1074**
			Total	3996	**3853**

[1] Excludes 1296 bad or invalid email addresses and 18 responses from retirees who indicated they were no longer teaching.
[†] Includes respondents who completed both introductory and majors sections and respondents who partially completed the introductory section.
[§] Includes respondents who only partially completed the introductory section.

TABLE S4. DISTRIBUTION BY INSTITUTION TYPE

Survey year	AA/AS	BA/BS	MS	PhD/ research	Other/ unknown
2004	0.1%	9.2%	24.0%	66.6%	0.0%
2009	4.7%	11.3%	22.6%	61.1%	0.3%
2012	26.3%	11.6%	22.8%	38.8%	0.5%
2016	23.2%	10.6%	21.1%	44.8%	0.5%
Total	14.2%	10.8%	22.6%	52.2%	0.3%
Syllabi	29.1%	12.3%	28.2%	25.0%	5.5%
AGI (2006)	16%	56%		23%	

TABLE S5. ACTIVITIES BY CLASS SIZE (2016 SURVEY)

Activity	**Frequency of use**	**Small:** 30 or fewer	**Medium:** 31-80	**Large:** More than 80
In-class activities	Never	12.0%	15.6%	29.6%*
	Once or twice	11.2%	14.7%	14.2%
	Several times	27.3%	31.4%	24.2%
	Weekly	27.0%	23.1%	19.6%
	Every class	22.5%*	15.3%	12.5%
Small-group discussion	Never	18.8%*	27.6%	29.9%
	Once or twice	19.8%	15.6%	20.1%
	Several times	23.7%	18.8%	19.7%
	Weekly	20.7%	20.2%	15.8%
	Every class	17.0%	17.9%	14.5%
Whole-group discussion	Never	12.9%*	20.3%*	44.1%*
	Once or twice	18.5%*	27.2%*	19.7%
	Several times	32.4%*	26.1%	21.8%*
	Weekly	21.4%	16.9%	7.4%*
	Every class	14.8%*	9.5%	7.0%*

* proportions that are statistically significantly different from other class sizes ($p < 0.05$)

TABLE S6. USE OF TEAMS BY CLASS SIZE (2016 SURVEY)

Activity	**Frequency of use**	**Small:** 30 or fewer	**Medium:** 31-80	**Large:** More than 80
Use of Teams	Never	8.7%*	17.5%*	29.1%*
	Once or twice	25.2%	25.1%	27.8%
	Three or more times	66.1%*	57.5%*	43.0%*