**PRACTICES FOR K-12 SCIENCE CLASSROOMS**

1. Asking questions (for science) and defining problems (for engineering)

2. Developing and using models

3. Planning and carrying out investigations

4. Analyzing and interpreting data

5. Using mathematics and computational thinking

6. Constructing explanations (for science) and designing solutions (for engineering)

7. Engaging in argument from evidence

8. Obtaining, evaluating, and communicating information

Practice 1 **Asking Questions and Defining Problems**

Questions are the engine that drives science and engineering.

Science asks

• What exists and what happens?

• Why does it happen?

• How does one know?

Engineering asks

• What can be done to address a particular human need or want?

• How can the need be better specified?

• What tools and technologies are available, or could be developed, for

addressing this need?

Both science and engineering ask

• How does one communicate about phenomena, evidence, explanations,

and design solutions?

Asking questions is essential to developing scientific habits of mind. Even

for individuals who do not become scientists or engineers, the ability to ask well-defined

questions is an important component of science literacy, helping to make

them critical consumers of scientific knowledge.

Scientific questions arise in a variety of ways. They can be driven by curiosity

about the world (e.g., Why is the sky blue?). They can be inspired by a model’s

or theory’s predictions or by attempts to extend or refine a model or theory (e.g.,

How does the particle model of matter explain the incompressibility of liquids?).

Or they can result from the need to provide better solutions to a problem. For

example, the question of why it is impossible to siphon water above a height of 32

feet led Evangelista Torricelli (17th-century inventor of the barometer) to his discoveries

about the atmosphere and the identification of a vacuum.

Questions are also important in engineering. Engineers must be able to ask

probing questions in order to define an engineering problem. For example, they

may ask: What is the need or desire that underlies the problem? What are the

criteria (specifications) for a successful solution? What are the constraints? Other

questions arise when generating possible solutions: Will this solution meet the

design criteria? Can two or more ideas be combined to produce a better solution?

What are the possible trade-offs? And more questions arise when testing solutions:

Which ideas should be tested? What evidence is needed to show which idea is

optimal under the given constraints?

The experience of learning science and engineering should therefore develop

students’ ability to ask—and indeed, encourage them to ask—well-formulated

questions that can be investigated empirically. Students also need to recognize the

distinction between questions that can be answered empirically and those that are

answerable only in other domains of knowledge or human experience.

GOALS

By grade 12, students should be able to

• Ask questions about the natural and human-built worlds—for example: Why

are there seasons? What do bees do? Why did that structure collapse? How

is electric power generated?

• Distinguish a scientific question (e.g., Why do helium balloons rise?) from a

nonscientific question (Which of these colored balloons is the prettiest?).

• Formulate and refine questions that can be answered empirically in a science

classroom and use them to design an inquiry or construct a pragmatic

solution.

• Ask probing questions that seek to identify the premises of an argument,

request further elaboration, refine a research question or engineering problem,

or challenge the interpretation of a data set—for example: How do you

know? What evidence supports that argument?

• Note features, patterns, or contradictions in observations and ask questions

about them.

• For engineering, ask questions about the need or desire to be met in order to

define constraints and specifications for a solution.

PROGRESSION

Students at any grade level should be able to ask questions of each other about the

texts they read, the features of the phenomena they observe, and the conclusions

they draw from their models or scientific investigations. For engineering, they

should ask questions to define the problem to be solved and to elicit ideas that

lead to the constraints and specifications for its solution. As they progress across

the grades, their questions should become more relevant, focused, and sophisticated.

Facilitating such evolution will require a classroom culture that respects and

values good questions, that offers students opportunities to refine their questions

and questioning strategies, and that incorporates the teaching of effective questioning

strategies across all grade levels. As a result, students will become increasingly

proficient at posing questions that request relevant empirical evidence; that

seek to refine a model, an explanation, or an engineering problem; or that challenge

the premise of an argument or the suitability of a design.

Practice 2 **Developing and Using Models**

construct mental and conceptual models of phenomena. Mental models

are internal, personal, idiosyncratic, incomplete, unstable, and essentially functional.

They serve the purpose of being a tool for thinking with, making predictions,

and making sense of experience. Conceptual models, the focus of this section, are,

in contrast, explicit representations that are in some ways analogous to the phenomena

they represent. Conceptual models allow scientists and engineers to better

visualize and understand a phenomenon under investigation or develop a possible

solution to a design problem. Used in science and engineering as either structural,

functional, or behavioral analogs, albeit simplified, conceptual models include diagrams,

physical replicas, mathematical representations, analogies, and computer

simulations. Although they do not correspond exactly to the more complicated

entity being modeled, they do bring certain features into focus while minimizing

or obscuring others. Because all models contain approximations and assumptions

that limit the range of validity of their application and the precision of their predictive

power, it is important to recognize their limitations.

Conceptual models are in some senses the external articulation of the mental

models that scientists hold and are strongly interrelated with mental models.

Building an understanding of models and their role in science helps students to

construct and revise mental models of phenomena. Better mental models, in turn,

lead to a deeper understanding of science and enhanced scientific reasoning.

GOALS

By grade 12, students should be able to

• Construct drawings or diagrams as representations of events or systems—for

example, draw a picture of an insect with labeled features, represent what

happens to the water in a puddle as it is warmed by the sun, or represent

a simple physical model of a real-world object and use it as the basis of an

explanation or to make predictions about how the system will behave in

specified circumstances.

• Represent and explain phenomena with multiple types of models—for example,

represent molecules with 3-D models or with bond diagrams—and move

flexibly between model types when different ones are most useful for different

purposes.

• Discuss the limitations and precision of a model as the representation of a

system, process, or design and suggest ways in which the model might be

improved to better fit available evidence or better reflect a design’s specifications.

Refine a model in light of empirical evidence or criticism to improve

its quality and explanatory power.

• Use (provided) computer simulations or simulations developed with simple

simulation tools as a tool for understanding and investigating aspects of a

system, particularly those not readily visible to the naked eye.

• Make and use a model to test a design, or aspects of a design, and to compare

the effectiveness of different design solutions.

PROGRESSION

Modeling can begin in the earliest grades, with students’ models progressing from

concrete “pictures” and/or physical scale models (e.g., a toy car) to more abstract

representations of relevant relationships in later grades, such as a diagram representing

forces on a particular object in a system. Students should be asked to use

diagrams, maps, and other abstract models as tools that enable them to elaborate

on their own ideas or findings and present them to others [15]. Young students

should be encouraged to devise pictorial and simple graphical representations of

the findings of their investigations and to use these models in developing their

explanations of what occurred.

More sophisticated types of models should increasingly be used across the

grades, both in instruction and curriculum materials, as students progress through

their science education. The quality of a student-developed model will be highly

dependent on prior knowledge and skill and also on the student’s understanding

of the system being modeled, so students should be expected to refine their

models as their understanding develops. Curricula will need to stress the role of

models explicitly and provide students with modeling tools (e.g., Model-It, agent-based

modeling such as NetLogo, spreadsheet models), so that students come to

value this core practice and develop a level of facility in constructing and applying

appropriate models.

Practice 3 **Planning and Carrying Out Investigations**

Scientists and engineers investigate and observe the world with essentially two

goals: (1) to systematically describe the world and (2) to develop and test theories

and explanations of how the world works. In the first, careful observation and

description often lead to identification of features that need to be explained or

questions that need to be explored.

The second goal requires investigations to test explanatory models of the

world and their predictions and whether the inferences suggested by these models

are supported by data. Planning and designing such investigations require the

ability to design experimental or observational inquiries that are appropriate to

answering the question being asked or testing a hypothesis that has been formed.

This process begins by identifying the relevant variables and considering how they

might be observed, measured, and controlled (constrained by the experimental

design to take particular values).

Planning for controls is an important part of the design of an investigation.

In laboratory experiments, it is critical to decide which variables are to be treated

as results or outputs and thus left to vary at will and which are to be treated as

input conditions and hence controlled. In many cases, particularly in the case of

field observations, such planning involves deciding what can be controlled and

how to collect different samples of data under different conditions, even though

not all conditions are under the direct control of the investigator.

Decisions must also be made about what measurements should be taken,

the level of accuracy required, and the kinds of instrumentation best suited to

making such measurements. As in other forms of inquiry, the key issue is one

of precision—the goal is to measure the variable as accurately as possible and

reduce sources of error. The investigator must therefore decide what constitutes

a sufficient level of precision and what techniques can be used to reduce both

random and systematic error.

GOALS

By grade 12, students should be able to

• Formulate a question that can be investigated within the scope of the classroom,

school laboratory, or field with available resources and, when appropriate,

frame a hypothesis (that is, a possible explanation that predicts a

particular and stable outcome) based on a model or theory.

• Decide what data are to be gathered, what tools are needed to do the gathering,

and how measurements will be recorded.

• Decide how much data are needed to produce reliable measurements and

consider any limitations on the precision of the data.

• Plan experimental or field-research procedures, identifying relevant independent

and dependent variables and, when appropriate, the need for controls.

• Consider possible confounding variables or effects and ensure that the investigation’s

design has controlled for them.

PROGRESSION

Students need opportunities to design investigations so that they can learn the

importance of such decisions as what to measure, what to keep constant, and how

to select or construct data collection instruments that are appropriate to the needs

of an inquiry. They also need experiences that help them recognize that the laboratory

is not the sole domain for legitimate scientific inquiry and that, for many scientists

(e.g., earth scientists, ethologists, ecologists), the “laboratory” is the natural

world where experiments are conducted and data are collected in the field.

In the elementary years, students’ experiences should be structured to help

them learn to define the features to be investigated, such as patterns that suggest

causal relationships (e.g., What features of a ramp affect the speed of a given

ball as it leaves the ramp?). The plan of the investigation, what trials to make

and how to record information about them, then needs to be refined iteratively

as students recognize from their experiences the limitations of their original plan.

These investigations can be enriched and extended by linking them to engineering

design projects—for example, how can students apply what they have learned

about ramps to design a track that makes a ball travel a given distance, go around

a loop, or stop on an uphill slope. From the earliest grades, students should have

opportunities to carry out careful and systematic investigations, with appropriately

supported prior experiences that develop their ability to observe and measure

and to record data using appropriate tools and instruments.

Students should have opportunities to plan and carry out several different

kinds of investigations during their K-12 years. At all levels, they should engage in

investigations that range from those structured by the teacher—in order to expose

an issue or question that they would be unlikely to explore on their own (e.g., measuring

specific properties of materials)—to those that emerge from students’ own questions. As they become more sophisticated, students also should have opportunities not only to identify questions to be researched but also to decide what data are to be gathered, what variables should be controlled, what tools or instruments are needed to gather and record data in an appropriate format, and eventually to consider how to incorporate measurement error in analyzing data.

Older students should be asked to develop a hypothesis that predicts a particular and stable outcome and to explain their reasoning and justify their choice. By high school, any hypothesis should be based on a well-developed model or theory. In addition, students should be able to recognize that it is not always possible to control variables and that other methods can be used in such cases—for example, looking for correlations (with the understanding that correlations do not necessarily imply causality).

Practice 4 **Analyzing and Interpreting Data**

Once collected, data must be presented in a form that can reveal any patterns and

relationships and that allows results to be communicated to others. Because raw

data as such have little meaning, a major practice of scientists is to organize and

interpret data through tabulating, graphing, or statistical analysis. Such analysis

can bring out the meaning of data—and their relevance—so that they may be used

as evidence.

Spreadsheets and databases provide useful ways of organizing data, especially

large data sets. The identification of relationships in data is aided by a range of

tools, including tables, graphs, and mathematics. Tables permit major features of

a large body of data to be summarized in a conveniently accessible form, graphs

offer a means of visually summarizing data, and mathematics is essential for

expressing relationships between different variables in the data set (see Practice 5

for further discussion of mathematics). Modern computer-based visualization tools

often allow data to be displayed in varied forms and thus for learners to engage

interactively with data in their analyses. In addition, standard statistical techniques

can help to reduce the effect of error in relating one variable to another.

Students need opportunities to analyze large data sets and identify correlations.

Increasingly, such data sets—involving temperature, pollution levels, and

other scientific measurements—are available on the Internet. Moreover, information

technology enables the capture of data beyond the classroom at all hours of

the day. Such data sets extend the range of students’ experiences and help to illuminate

this important practice of analyzing and interpreting data.

GOALS

By grade 12, students should be able to

• Analyze data systematically, either to look for salient patterns or to test

whether data are consistent with an initial hypothesis.

• Recognize when data are in conflict with expectations and consider what

revisions in the initial model are needed.

• Use spreadsheets, databases, tables, charts, graphs, statistics, mathematics,

and information and computer technology to collate, summarize, and

display data and to explore relationships between variables, especially those

representing input and output.

• Evaluate the strength of a conclusion that can be inferred from any data set,

using appropriate grade-level mathematical and statistical techniques.

• Recognize patterns in data that suggest relationships worth investigating further.

Distinguish between causal and correlational relationships.

• Collect data from physical models and analyze the performance of a design

under a range of conditions.

PROGRESSION

At the elementary level, students need support to recognize the need to record

observations—whether in drawings, words, or numbers—and to share them with

others. As they engage in scientific inquiry more deeply, they should begin to collect

categorical or numerical data for presentation in forms that facilitate interpretation,

such as tables and graphs. When feasible, computers and other digital tools

should be introduced as a means of enabling this practice.

In middle school, students should have opportunities to learn standard techniques

for displaying, analyzing, and interpreting data; such techniques include

different types of graphs, the identification of outliers in the data set, and averaging

to reduce the effects of measurement error. Students should also be asked to

explain why these techniques are needed.

As students progress through various science classes in high school and

their investigations become more complex, they need to develop skill in additional

techniques for displaying and analyzing data, such as x-y scatterplots or cross-tabulations

to express the relationship between two variables. Students should be

helped to recognize that they may need to explore more than one way to display

their data in order to identify and present significant features. They also need

opportunities to use mathematics and statistics to analyze features of data such as

covariation. Also at the high school level, students should have the opportunity to

use a greater diversity of samples of scientific data and to use computers or other

digital tools to support this kind of analysis.

Students should be expected to use some of these same techniques in engineering

as well. When they do so, it is important that they are made cognizant of

the purpose of the exercise—that any data they collect and analyze are intended to

help validate or improve a design or decide on an optimal solution.

Practice 5 **Using Mathematics and Computational Thinking**

Mathematics and computational tools are central to science and engineering. Mathematics enables the numerical representation of variables, the symbolic representation of relationships between physical entities, and the prediction of outcomes. Mathematics provides powerful models for describing and predicting such phenomena as atomic structure, gravitational forces, and quantum mechanics. Since the mid-20th century, computational theories, information and computer technologies, and algorithms have revolutionized virtually all scientific and engineering fields. These tools and strategies allow scientists and engineers to collect and analyze large data sets, search for distinctive patterns, and identify relationships and significant

features in ways that were previously impossible. They also provide powerful new techniques for employing mathematics to model complex phenomena—for example, the circulation of carbon dioxide in the atmosphere and ocean.

Mathematics and computation can be powerful tools when brought to

bear in a scientific investigation. Mathematics serves pragmatic functions as a

tool—both a communicative function, as one of the languages of science, and

a structural function, which allows for logical deduction. Mathematics enables

ideas to be expressed in a precise form and enables the identification of new ideas

about the physical world. For example, the concept of the equivalence of mass

and energy emerged from the mathematical analysis conducted by Einstein, based

on the premises of special relativity. The contemporary understanding of electromagnetic

waves emerged from Maxwell’s mathematical analysis of the behavior of

electric and magnetic fields. Modern theoretical physics is so heavily imbued with

mathematics that it would make no sense to try to divide it into mathematical and

nonmathematical parts. In much of modern science, predictions and inferences

have a probabilistic nature, so understanding the mathematics of probability and

of statistically derived inferences is an important part of understanding science.

Computational tools enhance the power of mathematics by enabling calculations

that cannot be carried out analytically. For example, they allow the

development of simulations, which combine mathematical representations of

multiple underlying phenomena to model the dynamics of a complex system.

Computational methods are also potent tools for visually representing data, and

they can show the results of calculations or simulations in ways that allow the

exploration of patterns.

Mathematics (including statistics) and computational tools are essential

for data analysis, especially for large data sets. The abilities to view data from

different perspectives and with different graphical representations, to test relationships

between variables, and to explore the interplay of diverse external

conditions all require mathematical skills that are enhanced and extended with

computational skills.

GOALS

By grade 12, students should be able to

• Recognize dimensional quantities and use appropriate units in scientific

applications of mathematical formulas and graphs.

• Express relationships and quantities in appropriate mathematical or algorithmic

forms for scientific modeling and investigations.

• Recognize that computer simulations are built on mathematical models that

incorporate underlying assumptions about the phenomena or systems being

studied.

• Use simple test cases of mathematical expressions, computer programs, or

simulations—that is, compare their outcomes with what is known about the

real world—to see if they “make sense.”

• Use grade-level-appropriate understanding of mathematics and statistics in

analyzing data.

PROGRESSION

Increasing students’ familiarity with the role of mathematics in science is central

to developing a deeper understanding of how science works. As soon as students

learn to count, they can begin using numbers to find or describe patterns in

nature. At appropriate grade levels, they should learn to use such instruments as

rulers, protractors, and thermometers for the measurement of variables that are

best represented by a continuous numerical scale, to apply mathematics to interpolate

values, and to identify features—such as maximum, minimum, range, average,

and median—of simple data sets.

A significant advance comes when relationships are expressed using equalities

first in words and then in algebraic symbols—for example, shifting from distance

traveled equals velocity multiplied by time elapsed to *s* = *vt*. Students should

have opportunities to explore how such symbolic representations can be used to

represent data, to predict outcomes, and eventually to derive further relationships

using mathematics. Students should gain experience in using computers to record

measurements taken with computer-connected probes or instruments, thereby recognizing

how this process allows multiple measurements to be made rapidly and

recurrently. Likewise, students should gain experience in using computer programs

to transform their data between various tabular and graphical forms, thereby aiding

in the identification of patterns.

Students should thus be encouraged to explore the use of computers for

data analysis, using simple data sets, at an early age. For example, they could

use spreadsheets to record data and then perform simple and recurring calculations

from those data, such as the calculation of average speed from measurements

of positions at multiple times. Later work should introduce them to the

use of mathematical relationships to build simple computer models, using

appropriate supporting programs or information and computer technology tools.

As students progress in their understanding of mathematics and computation, at

every level the science classroom should be a place where these tools are progressively

exploited.

Practice 6 **Constructing Explanations and Designing Solutions**

Because science seeks to enhance human understanding of the world, scientific theories are developed to provide explanations aimed at illuminating the nature of particular phenomena, predicting future events, or making inferences about past events. Science has developed explanatory theories, such as the germ theory of disease, the Big Bang theory of the origin of the universe, and Darwin’s theory of the evolution of species. Although their role is often misunderstood—the informal use of the word “theory,” after all, can mean a guess—*scientific* theories are constructs based on significant bodies of knowledge and evidence, are revised in light of new evidence, and must withstand significant scrutiny by the scientific community before they are widely accepted and applied. Theories are not mere guesses, and they are especially valued because they provide explanations for multiple instances.

In science, the term “hypothesis” is also used differently than it is in everyday language. A scientific hypothesis is neither a scientific theory nor a guess; it is a plausible explanation for an observed phenomenon that can predict what will happen in a given situation. A hypothesis is made based on existing theoretical understanding relevant to the situation and often also on a specific model for the system in question.

Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them. Very often the theory is first represented by a specific model for the situation in question, and then a model-based explanation is developed. For example, if one understands the theory of how oxygen is

obtained, transported, and utilized in the body, then a model of the circulatory system can be developed and used to explain why heart rate and breathing rate increase with exercise.

Engaging students with standard scientific explanations of the world— helping them to gain an understanding of the major ideas that science has developed— is a central aspect of science education. Asking students to demonstrate their own understanding of the implications of a scientific idea by developing their own explanations of phenomena, whether based on observations they have made or models they have developed, engages them in an essential part of the process by which conceptual change can occur. Explanations in science are a natural for such pedagogical uses, given their inherent appeals to simplicity, analogy, and empirical data (which may even be in the form of a thought experiment) [26, 27]. And explanations are especially valuable for the classroom because of, rather than in spite of, the fact that there often are competing explanations offered for the same phenomenon—for example, the recent gradual rise in the mean surface temperature on Earth. Deciding on the best explanation is a matter of argument that is resolved by how well any given explanation fits with all available data, how much it simplifies what would seem to be complex, and whether it produces a sense of understanding.

GOALS

By grade 12, students should be able to

• Construct their own explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence.

• Use primary or secondary scientific evidence and models to support or refute

an explanatory account of a phenomenon.

• Offer causal explanations appropriate to their level of scientific knowledge.

• Identify gaps or weaknesses in explanatory accounts (their own or those of

others).

In their experience of engineering, students should have the opportunity to

• Solve design problems by appropriately applying their scientific knowledge.

• Undertake design projects, engaging in all steps of the design cycle and producing

a plan that meets specific design criteria.

• Construct a device or implement a design solution.

• Evaluate and critique competing design solutions based on jointly developed

and agreed-on design criteria.

PROGRESSION

Early in their science education, students need opportunities to engage in constructing

and critiquing explanations. They should be encouraged to develop explanations of what they observe when conducting their own investigations and to evaluate their own and others’ explanations for consistency with the evidence. For example, observations of the owl pellets they dissect should lead them to produce an explanation of owls’ eating habits based on inferences made from what they find.

As students’ knowledge develops, they can begin to identify and isolate variables and incorporate the resulting observations into their explanations of phenomena. Using their measurements of how one factor does or does not affect another, they can develop causal accounts to explain what they observe. For example, in investigating the conditions under which plants grow fastest, they may notice that the plants die when kept in the dark and seek to develop an explanation for this finding. Although the explanation at this level may be as simple as “plants die in the dark because they need light in order to live and grow,” it provides

a basis for further questions and deeper understanding of how plants utilize light that can be developed in later grades. On the basis of comparison of their explanation with their observations, students can appreciate that an explanation such as “plants need light to grow” fails to explain why they die when no water is provided. They should be encouraged to revisit their initial ideas and produce more complete explanations that account for more of their observations.

By the middle grades, students recognize that many of the explanations of science rely on models or representations of entities that are too small to see or too large to visualize. For example, explaining why the temperature of water does not increase beyond 100°C when heated requires students to envisage water as consisting of microscopic particles and that the energy provided by heating can allow fast-moving particles to escape despite the force of attraction holding the particles together. In the later stages of their education, students should also progress to using mathematics or simulations to construct an explanation for a phenomenon.

Practice 7 **Engaging in Argument from Evidence**

Whether they concern new theories, proposed explanations of phenomena, novel

solutions to technological problems, or fresh interpretations of old data, scientists

and engineers use reasoning and argumentation to make their case. In science, the

production of knowledge is dependent on a process of reasoning that requires a

scientist to make a justified claim about the world. In response, other scientists

attempt to identify the claim’s weaknesses and limitations. Their arguments can be

based on deductions from premises, on inductive generalizations of existing patterns,

or on inferences about the best possible explanation. Argumentation is also

needed to resolve questions involving, for example, the best experimental design,

the most appropriate techniques of data analysis, or the best interpretation of a

given data set.

In short, science is replete with arguments that take place both informally, in

lab meetings and symposia, and formally, in peer review. Historical case studies of

the origin and development of a scientific idea show how a new idea is often difficult

to accept and has to be argued for—archetypal examples are the Copernican

idea that Earth travels around the sun and Darwin’s ideas about the origin of species.

Over time, ideas that survive critical examination even in the light of new

data attain consensual acceptance in the community, and by this process of discourse

and argument science maintains its objectivity and progress [28].

The knowledge and ability to detect “bad science” [29, 30] are requirements

both for the scientist and the citizen. Scientists must make critical judgments about

their own work and that of their peers, and the scientist and the citizen alike must

make evaluative judgments about the validity of science-related media reports

and their implications fo

r people’s own lives and society [30]. Becoming a critical

consumer of science is fostered by opportunities to use critique and evaluation to

judge the merits of any scientifically based argument.

GOALS

By grade 12, students should be able to

• Construct a scientific argument showing how data support a claim.

• Identify possible weaknesses in scientific arguments, appropriate to the students’

level of knowledge, and discuss them using reasoning and evidence.

• Identify flaws in their own arguments and modify and improve them in

response to criticism.

• Recognize that the major features of scientific arguments are claims, data,

and reasons and distinguish these elements in examples.

• Explain the nature of the controversy in the development of a given scientific

idea, describe the debate that surrounded its inception, and indicate why one

particular theory succeeded.

• Explain how claims to knowledge are judged by the scientific community

today and articulate the merits and limitations of peer review and the need

for independent replication of critical investigations.

• Read media reports of science or technology in a critical manner so as to

identify their strengths and weaknesses.

PROGRESSION

The study of science and engineering should produce a sense of the process of

argument necessary for advancing and defending a new idea or an explanation

of a phenomenon and the norms for conducting such arguments. In that spirit,

students should argue for the explanations they construct, defend their interpretations

of the associated data, and advocate for the designs they propose.

Meanwhile, they should learn how to evaluate critically the scientific arguments

of others and present counterarguments. Learning to argue scientifically offers

students not only an opportunity to use their scientific knowledge in justifying an

explanation and in identifying the weaknesses in others’ arguments but also to

build their own knowledge and understanding. Constructing and critiquing arguments

are both a core process of science and one that supports science education,

as research suggests that interaction with others is the most cognitively effective

way of learning [31-33].

Young students can begin by constructing an argument for their own

interpretation of the phenomena they observe and of any data they collect.

They need instructional support to go beyond simply making claims—that is, to

include reasons or references to evidence and to begin to distinguish evidence

from opinion. As they grow in their ability to construct scientific arguments,

students can draw on a wider range of reasons or evidence, so that their arguments

become more sophisticated. In addition, they should be expected to discern

what aspects of the evidence are potentially significant for supporting or

refuting a particular argument.

Students should begin learning to critique by asking questions about their

own findings and those of others. Later, they should be expected to identify possible

weaknesses in either data or an argument and explain why their criticism is

justified. As they become more adept at arguing and critiquing, they should be

introduced to the language needed to talk about argument, such as claim, reason,

data, etc. Exploration of historical episodes in science can provide opportunities

for students to identify the ideas, evidence, and arguments of professional scientists.

In so doing, they should be encouraged to recognize the criteria used to judge

claims for new knowledge and the formal means by which scientific ideas are

evaluated today. In particular, they should see how the practice of peer review and

independent verification of claimed experimental results help to maintain objectivity

and trust in science.

Practice 8 **Obtaining, Evaluating, and Communicating Information**

Being literate in science and engineering requires the ability to read and understand

their literatures [34]. Science and engineering are ways of knowing that

are represented and communicated by words, diagrams, charts, graphs, images,

symbols, and mathematics [35]. Reading, interpreting, and producing text\* are

fundamental practices of science in particular, and they constitute at least half of

engineers’ and scientists’ total working time [36].

Even when students have developed grade-level-appropriate reading skills,

reading in science is often challenging to students for three reasons. First, the

jargon of science texts is essentially unfamiliar; together with their often extensive

use of, for example, the passive voice and complex sentence structure, many

find these texts inaccessible [37]. Second, science texts must be read so as to

extract information accurately. Because the precise meaning of each word or

clause may be important, such texts require a mode of reading that is quite different

from reading a novel or even a newspaper. Third, science texts are multimodal

[38], using a mix of words, diagrams, charts, symbols, and mathematics

to communicate. Thus understanding science texts requires much more than simply

knowing the meanings of technical terms.

Communicating in written or spoken form is another fundamental practice of

science; it requires scientists to describe observations precisely, clarify their thinking,

and justify their arguments. Because writing is one of the primary means of com-

municating in the scientific community, learning how to produce scientific texts is

as essential to developing an understanding of science as learning how to draw is

to appreciating the skill of the visual artist. Indeed, the new *Common Core State*

*Standards for English Language Arts & Literacy in History/Social Studies, Science,*

*and Technical Subjects* [39] recognize that reading and writing skills are essential to

science; the formal inclusion in this framework of this science practice reinforces and

expands on that view. Science simply cannot advance if scientists are unable to communicate

their findings clearly and persuasively. Communication occurs in a variety

of formal venues, including peer-reviewed journals, books, conference presentations,

and carefully constructed websites; it occurs as well through informal means,

such as discussions, email messages, phone calls, and blogs. New technologies have

extended communicative practices, enabling multidisciplinary collaborations across

the globe that place even more emphasis on reading and writing. Increasingly, too,

scientists are required to engage in dialogues with lay audiences about their work,

which requires especially good communication skills.

Being a critical consumer of science and the products of engineering, whether as

a lay citizen or a practicing scientist or an engineer, also requires the ability to read or

view reports about science in the press or on the Internet and to recognize the salient

science, identify sources of error and methodological flaws, and distinguish observations

from inferences, arguments from explanations, and claims from evidence. All of

these are constructs learned from engaging in a critical discourse around texts.

Engineering proceeds in a similar manner because engineers need to communicate

ideas and find and exchange information—for example, about new techniques

or new uses of existing tools and materials. As in science, engineering communication

involves not just written and spoken language; many engineering ideas are best

communicated through sketches, diagrams, graphs, models, and products. Also

in wide use are handbooks, specific to particular engineering fields, that provide

detailed information, often in tabular form, on how best to formulate design solutions

to commonly encountered engineering tasks. Knowing how to seek and use

such informational resources is an important part of the engineer’s skill set.

GOALS

By grade 12, students should be able to

• Use words, tables, diagrams, and graphs (whether in hard copy or electronically),

as well as mathematical expressions, to communicate their understanding

or to ask questions about a system under study.

• Read scientific and engineering text, including tables, diagrams, and graphs,

commensurate with their scientific knowledge and explain the key ideas

being communicated.

• Recognize the major features of scientific and engineering writing and speaking

and be able to produce written and illustrated text or oral presentations

that communicate their own ideas and accomplishments.

• Engage in a critical reading of primary scientific literature (adapted for classroom

use) or of media reports of science and discuss the validity and reliability

of the data, hypotheses, and conclusions.

PROGRESSION

Any education in science and engineering needs to develop students’ ability to read

and produce domain-specific text. As such, every science or engineering lesson is

in part a language lesson, particularly reading and producing the genres of texts

that are intrinsic to science and engineering.

Students need sustained practice and support to develop the ability to

extract the meaning of scientific text from books, media reports, and other forms

of scientific communication because the form of this text is initially unfamiliar—

expository rather than narrative, often linguistically dense, and reliant on precise

logical flows. Students should be able to interpret meaning from text, to produce

text in which written language and diagrams are used to express scientific ideas,

and to engage in extended discussion about those ideas.

From the very start of their science education, students should be asked to

engage in the communication of science, especially regarding the investigations they

are conducting and the observations they are making. Careful description of observations

and clear statement of ideas, with the ability to both refine a statement in

response to questions and to ask questions of others to achieve clarification of what

is being said begin at the earliest grades. Beginning in upper elementary and middle

school, the ability to interpret written materials becomes more important. Early

work on reading science texts should also include explicit instruction and practice

in interpreting tables, diagrams, and charts and coordinating information conveyed

by them with information in written text. Throughout their science education, students

are continually introduced to new terms, and the meanings of those terms can

be learned only through opportunities to use and apply them in their specific contexts.

Not only must students learn technical terms but also more general academic

language, such as “analyze” or “correlation,” which are not part of most students’

everyday vocabulary and thus need specific elaboration if they are to make sense of

scientific text. It follows that to master the reading of scientific material, students

need opportunities to engage with such text and to identify its major features; they

cannot be expected simply to apply reading skills learned elsewhere to master this

unfamiliar genre effectively.

Students should write accounts of their work, using journals to record

observations, thoughts, ideas, and models. They should be encouraged to create

diagrams and to represent data and observations with plots and tables, as well

as with written text, in these journals. They should also begin to produce reports

or posters that present their work to others. As students begin to read and write

more texts, the particular genres of scientific text—a report of an investigation,

an explanation with supporting argumentation, an experimental procedure—will

need to be introduced and their purpose explored. Furthermore, students should

have opportunities to engage in discussion about observations and explanations

and to make oral presentations of their results and conclusions as well as to

engage in appropriate discourse with other students by asking questions and discussing

issues raised in such presentations. Because the spoken language of such

discussions and presentations is as far from their everyday language as scientific

text is from a novel, the development both of written and spoken scientific explanation/

argumentation needs to proceed in parallel.

In high school, these practices should be further developed by providing

students with more complex texts and a wider range of text materials, such as

technical reports or scientific literature on the Internet. Moreover, students need

opportunities to read and discuss general media reports with a critical eye and to

read appropriate samples of adapted primary literature [40] to begin seeing how

science is communicated by science practitioners.