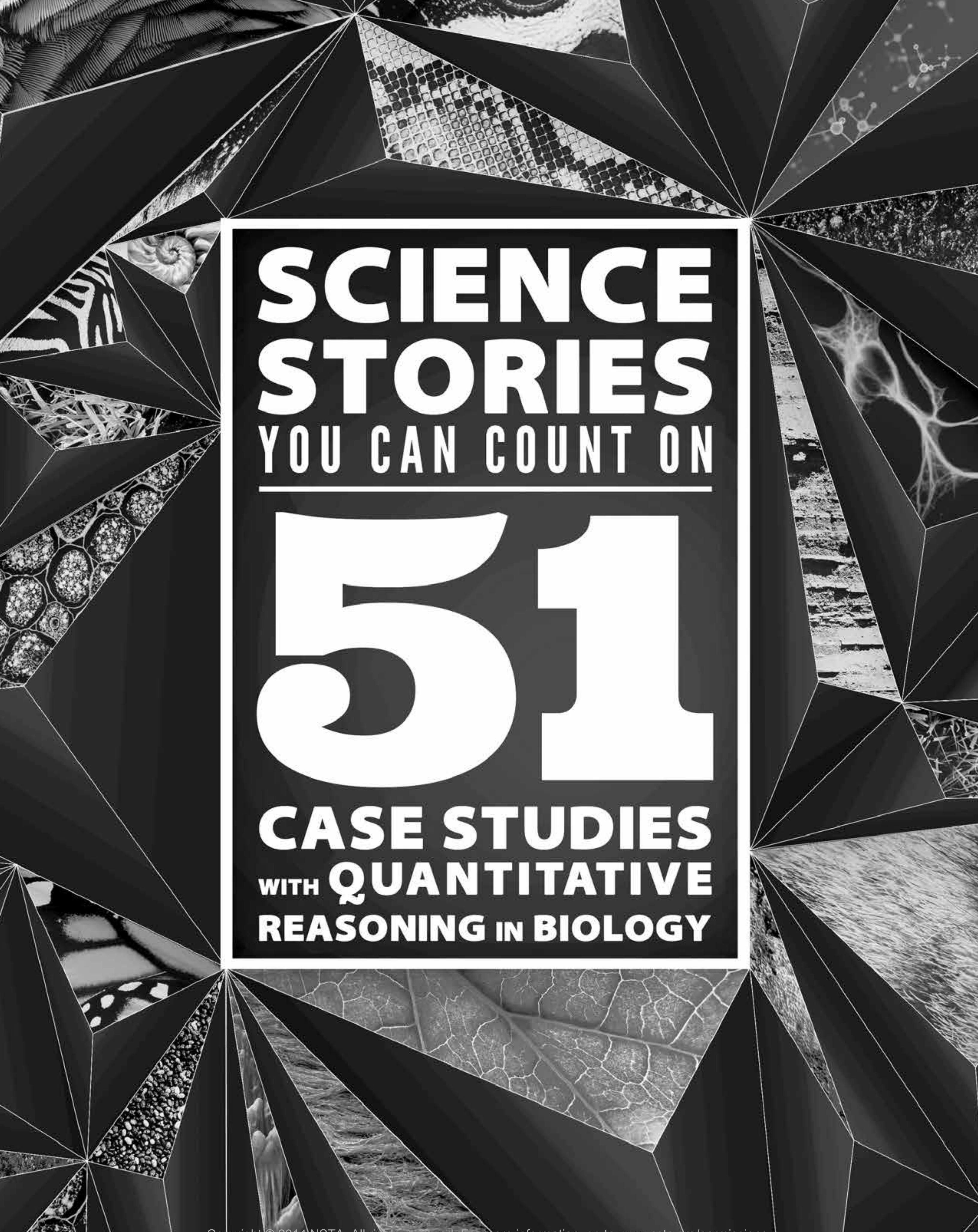
SCIENCE STORIES YOU CAN COUNT ON

51 CASE STUDIES WITH QUANTITATIVE REASONING IN BIOLOGY

CLYDE FREEMAN HERREID
NANCY A. SCHILLER
KY F. HERREID

NSTApress
National Science Teachers Association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INTRODUCTION
The Numbers Game

Clyde Freeman Herreid

There was a young man from Trinity,
Who solved the square root of infinity.
While counting the digits,
He was seized by the fidgets,
Dropped science, and took up divinity.
— *Author Unknown*

There was no need to do that. Drop science, that is. The young man from Trinity could have buckled down and learned the necessary mathematics to have a happy and fruitful career in science. He might even have discovered the physicists' version of the Holy Grail, the "Theory of Everything," or the answer to the biologist's head-scratching question of how consciousness arose. Then again, not everyone needs to be a scientist. In fact, C. P. Snow, British cultural raconteur and author of *The Two Cultures*, argued it would be downright dangerous. We need folks in the arts and humanities, and perhaps a philosopher or two is desirable. But even these individuals should be able to handle a bit of rudimentary mathematics, according to Snow, even the second law of thermodynamics! And if we believe the most recent behavioral studies, crows can count and so can pigeons, and mathematical calculations appear to be within the purview of even the lowly squid. Surely, we can expect as much from our undergraduates.

Our students should be able to at least reason quantitatively: to read and interpret data, graphs, and statistics. They should be astute enough to demand to see the evidence when some politician claims that a new drug cures cancer, job numbers are up, our carbon footprint is too big, the president's budget is the highest ever, and the world is coming to an end on December 21. And once having been shown the data, our intelligent citizen should not cringe if graphs stare him in the face, but fearlessly look at the data, and challenge the purveyor of false doctrines and celebrate the "truth-sayer" when found. But if this is a worthy ideal, how do we achieve numerical nirvana?

Traditional courses do not appear to achieve this ideal goal, for various reasons we will discuss in this chapter. We need to revise our approach to the required courses. In addition, we need to introduce quantitative skills throughout the curriculum as an integral part of courses, especially those that purport to teach STEM students.

Introductory biology seems an ideal place to start. Most students enroll in this course to fulfill their general elective credits required for graduation. They see it as a user-friendly science, integrating information from the physical sciences and the life sciences. Moreover, it is a gateway course for students on the way to health science careers. Teaching biology using real stories with quantitative reasoning skills enmeshed in the story line is a powerful and logical way to teach the subject and to show its relevance to the lives of future citizens, regardless of whether they are science specialists or laypeople. Yet the fundamental questions remain: What kind of education should a student have to deal with today's world? How much of it should focus on quantitative skills, and what kind of quantitative skills should we be teaching? And how should we do it?

Why Numeracy Matters

Numeracy means the ability to reason and to use numbers, and at its simplest level we are talking about arithmetic, adding, subtracting, multiplying, and dividing. This topic, why numeracy matters, was raised at the National Forum on Quantitative Literacy hosted by the National Academy of Sciences in Washington, D.C., on December 1–2, 2001. In the published proceedings (Madison and Steen 2003), Patricia Cohen gives us an historical perspective, reminding us that an informed and quantitatively literate society is essential for democracy. She notes that Massachusetts statesman Josiah Quincy wrote in 1816 about the "growing" importance of what he called the "art" of "Political Arithmetick." He "expounded on the connections … between statistical knowledge and 'the duties of citizens and lawmakers in the fledgling American republic'" (Cohen 2003, p. 7). Cohen notes in her essay that "Arithmetick" connects to democratic government in three distinct ways:

> First, the very political legitimacy of a representative democracy rests on repeated acts of counting: tallying people in periodic census enumerations to apportion the size and balance of legislative bodies, and tallying votes in varieties of elections to determine office-holding and public policies. Second, as Quincy suggested, a government whose goal is the general welfare of its citizens needs good aggregate information about those citizens on which to erect and assess public policy. It is no coincidence, then, that the word "statisticks" was coined in English in the 1790s…. And third, the citizens of democratic governments also need good information, to assess their leaders' political decisions and judge them on election day. (2003, p. 7)

The educational demands for a U.S. citizen have grown enormously since 1816, and the issue of how mathematics impacts our democracy is even more important today.

In their essay "The Democratization of Mathematics," Carnevale and Desrcochers (2003) write that our current system of teaching mathematics across the curriculum is flawed and threatens to undermine our democracy (p. 21). Mathematics acts as a filtering device, playing a significant role in who gets into the best colleges and the best professions even if higher level mathematics is not required for the day-to-day work in those fields:

> The sequence of abstract high school mathematics courses that prepares students for advanced degrees in mathematics and science is still crucial to our advanced economy, but moving the entire school-age population through the academic hierarchy from arithmetic to calculus as a sorting strategy for producing elite mathematical talent required of a small share of college majors and fewer than 5 percent of the workforce does not match well with our more general needs for applied reasoning abilities and practical numeracy …. It means making mathematics more accessible and responsive to the needs of all students, citizens, and workers. The essential challenge in democratizing mathematics applies to the sciences and humanities as well. The challenge is to match curricula to cultural, political, and economic goals rather than continuing the dominance of discrete disciplinary silos. (pp. 28–29)

The obvious follow-up question is tackled by Arnold Packer (2003) in his essay "What Mathematics Should 'Everyone' Know and Be Able to Do?" Packer asks rhetorically, what is wrong with the present system and then answers: "The way middle school teachers teach fractions provides a clue. They teach their students to add fractions by: First finding the lowest common denominator. Then converting all fractions to that denominator. Then adding the numerators. Finally, reducing the answer, if possible" (p. 34). As Packer goes on to point out, "Nobody does that outside the schoolroom. Imagine a school cafeteria in which the selected items totaled three quarters and three dollars and four dimes. The schoolroom method would be to change all these in for nickels."

What Kinds of Quantitative Skills?

Quantitative literacy and the need for a general education that includes some quantitative reasoning are important. It seems clear that we need to revise the way we teach these skills, placing greater emphasis on practical applications rather than abstract principles. This is the position of the National Council of Teachers of Mathematics (NCTM), which urges teachers to include real-world problem solving into their lesson plans and the need for students to be able to communicate in the language of mathematics (NCTM 2012). But if some quantitative skills are needed for the general public, they are even more important for students entering the fields of science and engineering.

In this section, we take a look at how the K–12 and college communities are grappling with these issues. A number of organizations and committees whose business it is to set standards have been active in this area. In reviewing the educational standards and goals for K–12 and college science education, we find many similarities. Our focus in this book is on the quantitative skills that people training to be biologists need to master. However, we cannot neglect secondary and postsecondary students, for they are all likely to stream through the general biology course, either because it is required for their major or because they have chosen the course as a general education requirement.

After we summarize the requirements, we turn to the question: What can we do in these introductory biology courses to enhance the quantitative skills of the students? We advocate the use of real-world problems, or cases, that teach quantitative skills to students in introductory biology courses via active learning strategies. We have been pioneers in the use of case study teaching for 20 years. In that time, many studies have supported our contention that teaching in context improves learning. Consistent with this view, this book offers many different examples of cases that have been tested in the classroom by both high school and college instructors. Before turning to those examples, let us see what various communities of scholars say about the foundational knowledge and skills students should acquire at different levels of their education. But it will be evident that the definition of numeracy depends upon the educational level considered and the career aspirations of the individual.

K–12 Students

The Committee on Conceptual Framework for the New K–12 Science Education Standards under the direction of the National Academies has recently published *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC 2012). They state: "We consider eight practices to be essential elements of the K–12 science and engineering curriculum:

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, information and computer technology, 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." (p. 49).

But, of course, the real issue is: How will the school systems implement these elements? For an answer, let's refer to the details of the framework. Here is the overarching vision:

> By the end of the 12th grade, students should have gained sufficient knowledge of the practices, crosscutting concepts, and core ideas of science and engineering to engage in public discussions on science-related issues, to be critical consumers of scientific information related to their everyday lives, and to continue to learn about

science throughout their lives. They should come to appreciate that science and the current scientific understanding of the world are the result of many hundreds of years of creative human endeavor. It is especially important to note that the above goals are for all students, not just those who pursue careers in science, engineering, or technology or those who continue on to higher education. (p. 9)

For our purposes, let's look closer at what they have to say about practices 4 and 5:

Practice 4: Analyzing and Interpreting Data (pp. 61–63)

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 the data through tabulating, graphing, or statistical analysis. Such analysis can bring out the meaning of the data—and their relevance—so that they may be used as evidence…

Goals

By grade 12, students should be able to:

- Analyze data systematically, either to look for salient patterns or to test whether the 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 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.

Practice 5: Using Mathematics and Computational Thinking (pp. 65–66)

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.

The material above has been extracted from a large document and the original version should be consulted in order to get the full flavor of the discussion. Further, the *Framework* does not specify a list of standards; rather, it sets forth an overarching vision for achieving quantitative literacy that makes sense at this time in history. Nor does the document give suggestions about how we can reach the stated goals; no specific courses are prescribed. Individual school systems and statewide recommendations are left to their own devices.

Keeping that in mind, let us turn to the standards initiative adopted by 45 states (*www.corestandards.org*). The *Common Core State Standards for Mathematics* (National Governors Association Center for Best Practices 2010) describes the concepts that students should know in mathematics at each grade level. Although they do not specify how these objectives should be reached, they do provide four model pathways that are used by various school systems. State school districts are now grappling with how they wish to implement the standards. New York and other states have adopted the traditional approach, which consists of two algebra courses and a geometry course, with some data, probability, and statistics included in each course (see *www.p12.nysed.gov/ciai/common_core_standards/pdfdocs/ccssi_mathematics_appendix_a.pdf*). Nonetheless, these courses with their familiar titles do not have to be traditional at all, as we will soon discover.

College Non-Science Majors

Many individuals and organizations have grappled with the question of what quantitative skills college students will need to achieve quantitative literacy (NRC 2003; AAAS 2009). An outstanding collection of papers have documented how various schools have attempted to overcome our mathematical illiteracy (*CBE – Life Sciences Education* 2010). In these 17 articles, 7 essays, and 7 features, we find multiple ways to infuse undergraduate biology with math and computational science. The Association of American Colleges and Universities (AACU) has even developed a rubric for quantitative literacy (*www.aacu.org/value/rubrics/pdf/QuantitativeLiteracy.pdf*). One cannot help but be impressed by the innovative solutions that faculty have come up with, but these are the exceptions.

Too commonly we find that when a school decides that they must overhaul their math requirements, they turn the problem over to their academic departments to mandate which courses they will accept for graduation. Not surprisingly, they often choose a selection of traditional math courses already in existence. The General Education Committees follow suit: They select pre-existing courses from the institution catalogue. Seldom do you find a faculty or an administration willing to start from scratch and work out which quantitative skills they think students need and then refurbish the curriculum.

Carleton College is an interesting exception. They have institutionalized a different approach to quantitative reasoning (QR), which they define as "the habit of mind to consider the power and limitations of quantitative evidence in the evaluation, construction, and communication of arguments in public, professional, and personal life" (Carleton College 2011a). They have attacked the problem head-on with their Quantitative Inquiry, Reasoning, and Knowledge (QuIRK) Initiative. Basically, the program has encouraged a wholesale, schoolwide overhaul of many courses to include quantitative skills in the course work. The school has a website that lists "Ten Foundational Quantitative Reasoning Questions," written by psychology professor Neil Lutsky, which Carleton College wants their students to be able to ask when confronted with data (Carleton College 2011b):

I. What do the numbers show?

- What do the numbers mean?
- Where are the numbers?
    - Is there numerical evidence to support a claim?
    - What were the exact figures?
    - How can seeking and analyzing numbers illuminate important phenomena?
- How plausible is a possibility in light of back-of-the-envelope calculations?

II. How representative is that?

- What's the central tendency?
  - "For instance" is not proof; it is an example.
  - Mean, Mode, and Median.
- Interrogating averages:
  - Are there extreme scores?
  - Are there meaningful subgroups?
  - What's the variability (standard deviation)?
- What are the odds of that? What's the base rate?

III. Compared to what?

- What's the implicit or explicit frame of reference?
- What's the unit of measurement?
- Per what?
- What's the order of magnitude?
- Interrogating a graph:
  - What's the Y-axis? Is it zero-based?
  - Does it K.I.S.S., or is it filled with ChartJunk?

IV. Is the outcome statistically significant?

- Is the outcome unlikely to have come about by chance?
  - "Chance is lumpy."
  - Criterion of sufficient rarity due to chance: $p < .05$
- What does statistical significance mean, and what doesn't it mean?

V. What's the effect size?

- How can we take the measure of how substantial an outcome is?
- How large is the mean difference? How large is the association?
- Standardized mean difference (d): $d = (\mu 1 - \mu 2)/\sigma$

VI. Are the results those of a single study or from literature?

- What's the source of the numbers: PFA, peer-reviewed, or what?
- Who is sponsoring the research?

- How can we take the measure of what the literature shows?
- The importance of meta-analysis in the contemporary world of QR.

VII. What is the research design (correlational or experimental)?

- Design matters: Experimental vs. correlational design.
- How well does the design support a causal claim?
- Experimental Design:
    - Randomized Controlled Trials (RCT): Research trials in which participants are randomly assigned to the conditions of the study.
    - Double blind trials: RCTs in which neither the researcher nor the patient know the treatment condition.
- Correlational Design: Measuring existing variation and evaluating co-occurrences, possibly controlling for other variables.
    - Interrogating associations (correlations):
        - Are there extreme pairs of scores (outliers)?
        - Are there meaningful subgroups?
        - Is the range of scores in a variable restricted?
        - Is the relationship non-linear?

VIII. How was the variable operationalized?

- What meaning and degree of precision does the measurement procedure justify?
- What elements and procedures result in the assignment of a score to a variable?
- What exactly was asked?
- What's the scale of measurement?
- How might we know if the measurement procedure is a good one?
    - Reliability = Repeated applications of the procedure result in consistent scores.
    - Validity = Evidence supports the use to which the measure is being put.
- Is the measure being manipulated or "gamed"? The iatrogenic effects of measurement.

IX. Who's in the measurement sample?

- What domain is being evaluated? Who's in? Who's not?

- Is the sample from that domain representative, meaningful, and/or sufficient?
- Is the sample random?
- Are two or more samples that are being compared equivalent?

X. Controlling for what?

- What other variables might be influencing the findings?
- Were these assessed or otherwise controlled for in the research design?
- What don't we know, and how can we acknowledge uncertainties?

This seems to me to be an eminently reasonable approach to the question of what we wish every citizen to know. Unfortunately, our typical college courses don't come close to achieving these goals. Interestingly, nearly all of these topics are covered in a typical statistics course, yet most schools do not list statistics as a graduation requirement though many have it as an option. So if we really care about teaching our students to be "quantitative reasoners," how do we accomplish that?

A vote for statistics in the required curriculum comes from Marie Davidian and Thomas Louis in their editorial, "Why Statistics," which appeared in the April 6, 2012, issue of *Science*. They remind us that "Statistics is the science of learning from data, and of measuring, controlling, and communicating uncertainty; and it thereby provides the navigation essential for controlling the course of scientific and societal advances." They point out that statistics informs policy development in governmental budgets as well as medical discoveries and science advancement in general. They applaud the new U.S. Common Core K–12 Mathematics Standards, which introduces statistics as a key part of pre-college education, encompassing skills in describing data, developing statistical models, making inferences, and evaluating the consequences of decisions.

Ecologists Carol Brewer and Louis Gross (2003) foreshadowed these arguments, saying science students and the public should have an education that allows them to deal with uncertainty and variability so that they are better able to grapple with topics such as climate change. Ecologists require a background in probability, including the concepts of random variables, stochastic processes, and Bayesian statistics. But the general public needs an education as well, one that will allow them to appreciate important assumptions and limitations that are part of model building and the reasoning involved in predictive forecasting. Brewer and Gross argue that "regular exposure to probabilistic ideas (e.g., weather forecasts, lotteries) does not provide much of a basis for public appreciation of uncertainty in ecological forecasts …. Beyond formal training in schools and universities, education of the general public can be aided by targeted articles in the press, especially when they can be related to local or regional projects (e.g., restoration projects, land-use reviews) for which ecological projections inform decision-making. This implies that scientists involved in the development of these projections have an obligation to disseminate information at a level that is clear to a general audience" (p. 1413).

But they offer no panacea for how to accomplish this; they simply urge faculty to develop new course materials and attend workshops where the emphasis is on better communication of probabilistic models for future students. One solution to the problem has been touted by a group of instructors who teach mathematics using case studies that they have developed using material from newspapers (Madison et al. 2009).

Pre-Professional Health Students

An inordinate number of students in most introductory biology classes start college dreaming of a career in the medical, dental, pharmacy, nursing, physical therapy, or related health professions. In my general biology course, they make up about 80% of the population. Less than half of them survive the first two years' requirements.

In the March 30, 2012, issue of *Science*, S. James Gates and Chad Mirkin, members of the President's Council of Advisors on Science and Technology, noted that in the United States over 60% of the students who enter college intending to major in a STEM field fail to graduate with a STEM degree. (Read that again: *Over 60% of the students who enter college intending to major in a STEM field fail to graduate with a STEM degree!*) They report that students leave STEM during the first two years for three major reasons: uninspiring introductory courses, difficulty with the required math, and an academic culture in STEM fields that is unwelcoming. The problem is especially acute for women and minorities. (These comments resonate strongly with Sheila Tobias's 1990 and 1992 books on the topic 20 years ago.) Gates and Mirkin recommend that the "federal government catalyze widespread adoption of active learning approaches using case studies, problem-based learning, peer instruction, and computer simulations." They further emphasize hands-on research and laboratory experiences that begin early in the college career.

How do our current standard curricula stack up to the general criticisms made by the President's Council of Advisors? First, there is the problem that 86% of the natural sciences faculty say that lecturing is their primary method of instruction (National Research Council 2003). Then there are the math requirements. Let's take a look at what they are just for pre-professional health students. The curricula across the United States show little variation among schools and disciplines; they have not seriously changed over the last several decades.

From the American Association of Colleges of Pharmacy course requirements (AACP) for 2012–2013 (AACP 2012) we learn that 94% of the institutions require calculus, 60% require statistics, and 9% require computer science applications. Is this the curriculum that we think is ideal for training today's pharmacists—or, for that matter, for physicians, dentists, or for any health professionals? They have similar requirements for mathematics. Virtually everyone thinks they have to have calculus to get into professional health schools.

Appendix A gives a list of "Expectations for Medical Students" developed by the AAMC-HHMI Scientific Foundations for Future Physicians. But when we look at the desired competencies, there seems to be little need for the standard calculus course. Instead, we see statistics and data interpretation are eminently valued. Yet, courses in these subjects are not apparently on the list of required courses developed by the Association of American Medical Colleges. That seems odd.

What is it about calculus that makes it so desirable, when virtually none of the health practitioners will ever integrate or differentiate anything in their life? As a counterpoint: I have been assured by a dean of pharmacy that students in their PharmD program take pharmacokinetics where the kinetics of drug action does often involve differential equations. There are undoubtedly occasions in medical school where similar examples occur. But do students really need two semesters of calculus while statistics is left to languish?

Still, calculus may have unsuspected potential benefits. Philip Sadler and Robert Tai (2007) wondered if courses in high school affected students' grades in introductory college courses. They studied 8,474 undergraduate students enrolled in one of the three introductory science courses at 63 colleges and universities. Not surprisingly, students who had taken physics, chemistry, or biology in high school performed better in those respective subjects than those that did not. But they did not do better in other science subjects; that is, there was no cross-subject benefit for someone who took chemistry and thus improved their performance in say biology or physics. *But here is the kicker: The students who had taken high school calculus did better in the science subjects than those who did not.* This was true even if calculus was not part of the course curriculum in many of these courses. Was there something about the students who took calculus that brought about higher performance, or was it the course material itself that promoted better performance, or were there other causes at work? Cause/effect questions notwithstanding, the evidence is clear. Whatever brought this effect about, whether it was that taking calculus actually improved science performance or whether the effect was caused by another variable, we should take this result seriously and examine what is driving this correlation.

Professional Biologists

In a 2004 essay Joel E. Cohen emphasized the importance of mathematics to biology, making the point in his title: "Mathematics is Biology's Next Microscope, Only Better; Biology is Mathematics' Next Physics, Only Better." His points were these: Just as the microscope opened up new vistas for biology, mathematics has the potential to do even more for biology. Cohen reminds us that Mendel's discoveries of the general principles of genetics leaned heavily upon mathematics. William Harvey's calculations of blood flow were crucial to his understanding of human circulation. And dozens of other biological principles are undergirded by quantitative reasoning, including the Hardy-Weinberg Equilibrium of evolution, forensic analysis of DNA and the probability of parentage or criminal activity. Conversely, biology will promote new mathematical discoveries, just as Isaac Newton and Gottfried Leibniz were stimulated by physical problems such as planetary orbits and optical calculations and developed calculus. Hastings et al. (2000) in their NSF report *Quantitative Biology for the 21st Century* develops this thread in more detail, as does the National Academies Press publication, *BIO 2010: Transforming Undergraduate Education for Future Research Biologists* (NRC 2003).

What kind of quantitative skills do we want our biology majors to have if they intend to go to graduate school and become research scientists? The standard requirements at different schools include calculus, with statistics running a poor second. Unless a student has a strong penchant for mathematics or computer competency or is a quantitative masochist, that's it for our requirements. Most students take no more than the minimum.

BIO 2010 (extracts are reprinted in Appendix B) makes these points: (1) "In contrast to biological research, undergraduate biology education has changed relatively little during the past two decades. The ways in which most future research biologists are educated are geared to the biology of the past, rather than to the biology of the present or future" (p. 1). (2) "Much of today's biomedical research is at the interface between biology and the physical, mathematical, or information sciences. Most colleges and universities already require their biology majors to enroll in courses in mathematics and physical science. However, faculty often do not integrate these subjects into the biology courses they teach." (3) "Most biology majors take no more than one year of calculus, although some also take an additional semester of statistics …. While calculus remains an important topic for future biologists, the committee does not believe biology students should study calculus to the exclusion of other types of mathematics. Newly designed courses in mathematics that cover some calculus as well as the other types of math mentioned above would be suitable for biology majors and would also prove useful to students enrolled in many other undergraduate majors." (4) "One way to start is to add modules into existing biology courses. Throughout this report, modules are mentioned as a way to modify courses without completely revamping the syllabus." As an example of this, see the lab MathBench modules that have been developed by the University of Maryland (Thompson et al. 2010). Also note the BioQUEST site with modules on bioinformatics, quantitative biology, molecular biology, and the math behind biology (*http://bioquest.org*). Changes like these will require a major commitment of faculty and administrators, with faculty development being a central part of such a revolution.

What do I make of this? Most of our students in introductory science courses are not going to be scientists—it is not even a close call. They are just fulfilling a general education requirement, unless it is a course that is catering to biology majors or pre-professional health students. Since the overwhelming number of our students will never take another biology class, our goal in the introductory course should be to show students how science is really practiced and convey to them the excitement of the subject. Quantitative material should be introduced, but only in the context of the subject matter. We should leave the heavy-duty mathematics for the higher-level courses, but even then we should change what we are doing. Taking a page from *BIO 2010*, we should revamp or add modules to our courses by weaving quantitative skills into the material in the context of real-world problems. Moreover, since all schools insist that calculus is the *sine qua non* ingredient for any student who is considering anything remotely scientific, then surely the current course content should be changed. Too many calculus courses seem to emphasize memorizing a set of equations without any apparent connection to the real world; rather, they should be like the integrated two-semester course taught at the University of Tennessee that replaces the traditional calculus course (see Appendix B). This is "A new mathematics sequence that exposes students to statistics, probability, discrete math, linear algebra, calculus, and modeling without requiring that a full semester be spent on each topic." Other examples are presented in the series of articles in the special quantitative issue of the journal *CBE—Life Sciences Education* (2010). Especially note Marsteller et al.'s (2010) list of schools that are using biological examples to teach mathematical concepts and the inventory of colleges and universities with mathematical biology education modules.

Case Studies and Quantitative Literacy

Now we know several things. Experts believe that mathematics is important, not only for a well-rounded education but because they believe that quantitative literacy skills are essential to making intelligent decisions as citizens. Do students need more than the fundamentals taught in K–12? Some higher education institutions apparently do not think so, for they do not have any math requirements. Other schools, such as my own university, require only a semester of "mathematics" as part of their general education requirements. They include statistics as one of the alternatives, but there are more than 25 other possible options that fulfill the requirement! Obviously, the school does not have a clear vision of what constitutes quantitative literacy and has taken the easy way out of the potential controversy.

Nonetheless, there is a general consensus among the experts: If we are going to go with the standard courses that are on the books, then statistics is the one course that all students should have—scientists and laypersons alike. This point is made indirectly by the AAMC-HHMI report (Appendix A), which lists the course expectations for entering medical students. The same point is made explicitly by the CRAFTY Curriculum Foundations Project (Johnson, Peterson, and Yoshiwara 2002) recommending the courses for students graduating from two-year colleges in technical training. However, if we are going to develop a novel approach, then a practical one-semester course can do the job, such as the one used by the University of Arkansas where quantitative skills are taught via case studies from media sources (Madison et al. 2009; Dingman and Madison 2010; Madison and Dingman 2010).

As for most calculus courses, they are not germane to practically anyone. It is typically a plug and chug experience; i.e., they show you an equation; you memorize it, do a few problems, and then go on to the next equation. There are few opportunities for students to really use the skills on real problems they might encounter in the real world—and of course, few ever will. The course needs a major overhaul, perhaps merging other practical mathematics into a new applied course, such as taught at the University of Tennessee (see Appendix B, p. 513).

So here is the bottom line of this book. All students need some mathematics. They receive the fundamentals in their K–12 education. Once they are in higher education, the kind and extent of their quantitative instruction depends upon their career plans. This training should either be statistics or, even better, a specially designed course that deals with mathematics in an applied manner. This would be the end of most students' math education unless they are headed for specific fields like engineering or advanced fields in biology with a mathematical bent, such as ecology or computational biology. Here is the important point: It is especially important that all students, regardless of their major, leave school knowing what questions to ask when they see data rolled out, like the students graduating from Carleton College.

How can this best be achieved? One way to approach this is to use active learning such as case study teaching. And this can be done in all general science courses, introducing cases whenever possible that have quantitative problems embedded within them. Fortunately, several key resources exist, including websites where case studies can be downloaded along with teaching notes, such as the web-based case collection of the National Center for Case Study Teaching in Science (NCCSTS) at the University at Buffalo (*sciencecases.lib.buffalo.edu*). Currently, the NCCSTS website has about 500 case studies across all science disciplines. Other case collections include the Problem-Based Learning Clearinghouse at the University of Delaware (*https://pblc.nss.udel.edu/Pbl*), Emory University's CASES Online (*www.cse.emory.edu/cases*), and the interactive molecular biology laboratory simulations in the Case It! collection (*www.caseitproject.org*). Many of the cases on these sites have quantitative material, such as tables, graphs, numerical data, and equations that are essential to the case story.

This book includes cases selected from the National Center for Case Study Teaching in Science website (*http://sciencecaase.lib.buffalo.edu*) that develop students' quantitative skills and apply them to solve real-world problems. In this book we present each case along with a list of learning objectives for it. Detailed teaching notes for the cases can be found on our website along with answer keys, which instructors can register to access. The book is designed for college and high school AP biology teachers. We expect that teachers who plan to use the cases will download the case PDF from the website and distribute it to students in class rather than direct students to the website itself, where the teaching notes are displayed.*

The advantage of these cases is that they teach science in context, not as a set of abstract principles and a jumble of terms without rhyme or reason, but as part of a story so that students can see the relevance of the material. Moreover, in using cases to teach quantitative skills and show their applications to real-world situations, we are inculcating in our students the *practice* of questioning data, not just as a classroom exercise, but as a tool for engaging and understanding the world around them. K–12 teachers will find the cases in-line with the recommendations of the *Next Generation of Science Standards* (*www.nextgenscience.org/next-generation-science-standards*), which lists major biological topics as necessary parts of any curriculum: structure and function, matter and energy in organisms and ecosystems, interdependent relations in ecosystems, inheritance and variation of traits, natural selection and evolution, and understanding the nature of science. The cases included in this book also address the overarching framework presented in *Vision and Change in Undergraduate Biology Education: A Call to Action* (*http://visionandchange.org/files/2011/03/Revised-Vision-and-Change-Final-Report.pdf*), a document prepared by the National Science Foundation and the American Association for the Advancement of Science, which calls for enhanced quantitative and computational expertise in core competencies of biologists, "the ability to use quantitative reasoning" and "the ability to use modeling and simulation," to gain a deeper understanding of the dynamics and complexity of biological systems.

Our book is divided into sections. These mirror the topical sections one finds in many introductory biology textbooks. We have organized cases in the following areas: Scientific Method, Chemistry of Life, the Cell, Microbiology, Genetics, Molecular Biology, Evolution, Plant Form and Function, Animal Form and Function, Health, Ecology and Behavior, and Biosphere and Conservation. High school, community college, and undergraduate college teachers can use these cases to illustrate many of the basic principles of biology, but more importantly, how science is really conducted. The cases—most of which are based on real events and problems—should engage students and put quantitative skills to use, hopefully to illustrate just how necessary these competencies are to understanding our world, which is awash with numbers and people who are willing to exploit them for their own particular agendas.

*Teaching notes and answer keys for the case studies can be found at *www.nccsts.org/nsta_quant.html*. When you click on the links on that page, you will be asked to log in. For the username, enter "NSTA." For the password, use the second word in the first line of text that appears on page 191 of this book.

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A CAN OF BULL

Do Energy Drinks Really Provide a Source of Energy?

Merle Heidemann and Gerald Urquhart

Abstract

This case teaches students about large biomolecules, nutrition, and product analysis. Students conduct a biochemical analysis of several popular energy drinks on the market and determine whether these products nutritionally match their marketing claims.

Learning Objectives

- Describe and categorize chemically the components of various popular "energy drinks."
- Determine the physiological role of these components in the human body.
- Explain scientifically how the marketing claims for these drinks are supported (or not).
- Determine under what conditions each of the "energy drinks" might be useful to the consumer.
- Write an analysis of energy drinks for a popular magazine.

Quantitative Reasoning Skills/Concepts

- Articulate complete and correct claims based on data.
- Use appropriate reasoning to support the validity of data-based claims.

The Case Study

Case Scenario

After spending several years working the Sport's Desk of the *Lansing State Journal*, Rhonda had landed the job of her dreams as a writer for *Runners' World* magazine. The job was fantastic! Since high school, where she had excelled in cross country, Rhonda had been a consistent runner, participating in local races and those assigned to her for her job. For her last assignment, she had run and reported on the Leadwood, South Dakota, marathon—*it was a blast!*

As if reading her mind, her boss Charley walked in just then with a can of XS Citrus Blast® in one hand and a list of several other energy drinks in the other.

"We've been getting a lot of inquiries about the different energy drinks on the market, including XS Citrus Blast. Do you know anything about them?" Charley asked.

"I know that people use them for various reasons," replied Rhonda. "It seems they're primarily used by athletes to provide some 'fuel' as they practice and compete. Other people use them more casually as a way to become 'energized.' That's about all I know."

"That seems to be about all any of us knows," Charley said. "For your next assignment," Charley continued, "I want you to find out what each of the ingredients in these drinks is and what it does for a runner or for a non-athlete. You need to be very accurate in your analysis—determine what each component really does for the body, not what the marketers want you to believe it does. Then look at the marketing claims of some of these drinks and see if the scientific facts match up to them. Many of our readers are using these drinks with some general notion that they're helpful, but they're basing their use of them on no scientific information. I've got the marketing claims, a list of ingredients and nutrition facts provided on the cans for consumers, and a short list of questions that should get you started. When you research these, be sure to document all your sources of information, keeping in mind that all resources are not equal. Here's the information."

With that, Charley left the office. Rhonda looked over the list. "Guess I'll have to brush up on my biochemistry. No problem. I'm interested in knowing if my running would be improved by drinking this stuff." Rhonda recalled that a food's calorie content was the simplest reflection of its energy content. Looking at Charley's list she saw that the different energy drinks contained the *numbers of calories* in Table 11.1.

TABLE 11.1.

Calorie Content for a Sample of Energy Drinks.

Energy Drink	Calories
XS Citrus Blast®	8
Red Bull®	110
Sobe Adrenaline Rush®	140
Impulse®	110
For comparison: Coca Cola® (12 oz.)	140

Marketing Claims

Next, Rhonda perused the marketing claims for each drink, shown in Table 11.2.

TABLE 11.2.

Marketing Claims for a Sample of Energy Drinks.

Energy Drink	Marketing Claims
Red Bull	• The Red Bull energy drink is a functional product developed especially for periods of increased mental and physical exertion. • It can be drunk in virtually any situation: at sport, work, study, driving and socializing. • Improves performance, especially during times of increased stress or strain. • Improves concentration and reaction speed. • Stimulates the metabolism.
XS Citrus Blast	• There is less than 1/2 calorie of sugar in XS Citrus Blast. This qualifies for the government-approved statement “No Sugar.” The 8 calories in XS Citrus Blast are from amino acids and are protein calories that aid your body’s natural metabolic process. • Most 8-ounce energy drinks in the market today have over 100 calories and from 27 to 30 grams of sugar, which is a simple carbohydrate. Most 12-ounce non-diet soft drinks have 170 calories from 40 grams of sugar. Most 5.5-ounce juice drinks have 80 calories from 20 grams of sugar. • Calories from sugar and carbohydrates may increase fat deposits. Simple carbohydrates are also called high glycemic (high sugar) foods. High glycemic foods cause your body to pump insulin to digest the sugar, which sends a message to your body to store calories as fat. Low glycemic foods do not pump insulin to the same degree and aid in your body’s natural metabolism of fat, using your body’s fat resources as fuel. Many experts fear that the epidemic incidence of diabetes in North America today may be significantly contributed to by high-glycemic diets. The 8 calories in XS Citrus Blast are from amino acids and are protein calories that aid your body’s natural metabolic process. • XS Citrus Blast uses a proprietary blend of Sucralose, Acesulfame Potassium (Ace K), and fruit essences to give the drinks their great flavor without sugar or empty calories. In fact, the 8 calories in the drink come from the 2 grams of amino acids, which are protein calories.

Table 11.2 (*continued*)

Energy Drink	Marketing Claims
Sobe Adrenaline Rush	• This maximum energy supplement delivers an energy boost with a natural passion fruit flavor. It's lightly carbonated with a clean smooth feel. • This maximum energy supplement is fortified with a unique blend of natural energizing elements, including d-ribose, l-carnitine and taurine. It's pure, concentrated energy in an 8.3-fluid-ounce can.
Impulse	• Elevate Your Performance • Impulse Energy Drink contains special supplements to immediately enhance mental and physical efficiency and give you the energy boost you deserve… replenishing your strength. • Impulse gets its energy from a simple source: nutrients, minerals, and vitamins that occur naturally in the body and foods we eat. Enjoy: the wake-up power of caffeine, the alertness-inducing properties of taurine, the lift you get from vitamins B6 and B12. Combined with Impulse's other ingredients, these are known to increase mental focus and physical well-being, enhance performance, and accelerate metabolism.

Charley's List of Questions

Rhonda realized that before she could start analyzing the energy drinks, she needed to know the answer to the following question: "When we say that something gives us 'energy,' what does that mean? What is a biological definition of energy?"

After satisfying herself that she had a good definition, she turned to the first set of questions on Charley's list:

1. What is the nature (sugar, amino acid, vitamin, etc.) of each ingredient listed on the cans?
2. What is the physiological role of each in the human body?
3. Which ingredients provide energy?
4. Which ingredients contribute to body repair, i.e., which help build or rebuild muscle tissue?

Ingredients and Nutrition Facts

Rhonda was determined to wade through the confusing labeling of the drinks. For example, XS Citrus Blast boasted that it had no calories but still provided "energy." That made absolutely no sense based on what Rhonda knew about biological energy! The first thing she needed to do was sort out the various ingredients on the labels—a task that consumers rarely undertake. Her findings are summarized in Table 11.3. As in most labels, ingredients are listed in order of mass in drinks, from highest to lowest.

TABLE 11.3.

Energy Drink Ingredients and Nutrition Facts

Energy Drink	Ingredients and Nutrition Facts
XS Citrus Blast	• *Ingredients:* carbonated water, l-taurine, l-glutamine, citric acid, adaptogen blend (eleutherococcus senticosus, panax ginseng, panax quinquefolium, echinacea purpurea, schisandra, astragalus, and reishi), natural flavors, acesulfame potassium, caffeine, sodium benzoate, potassium sorbate, sucralose, niacin, pantothenic acid, pyridoxine HCL, yellow 5, cyanocobalamin • *Nutrition Facts:* serving size: 8.4 fl oz; servings per container: 1; calories: 8; fat: 0 g; sodium: 24 mg; potassium: 25 mg; total carbs: 0 g; sugars: 0 g; protein: 2 g; vitamin B3: 100%; vitamin B6: 300%; vitamin B5: 100%; vitamin B12: 4900%
Red Bull	• *Ingredients:* carbonated water, sucrose, glucose, sodium citrate, taurine, glucuronolactone, caffeine, inositol, niacin, D-pantothenol, pyridoxine HCL, vitamin B12, artificial flavors, colors • *Nutrition Facts:* serving size: 8.3 fl oz; servings per container: 1; amount per serving: calories: 110; total fat: 0 g; sodium: 200 mg; protein: 0 g; total carbohydrates: 28 g; sugars: 27 g
Sobe Adrenaline Rush	• *Ingredients:* filtered water, high fructose corn syrup, citric acid, taurine, d-ribose, l-carnitine, natural flavor, inositol, sodium citrate, ascorbic acid, caffeine, monopotassium phosphate, salt, gum arabic, ester gum, siberian ginseng root extract, pyridoxine hydrochloride, guarana seed extract, caramel color, beta-carotene, folic acid, cyanocobalamin • *Nutrition Facts:* serving size: 8.3 fl oz; servings per container: 1; amount per serving: calories: 140; total fat: 0 g; sodium: 60 mg; protein: 1 g; total carbohydrates: 36 g; sugars: 34 g; taurine: 1000 mg; d-ribose: 500 mg; l-carnitine: 250 mg; inositol: 100 mg; siberian ginseng: 50 mg; guarana: 50 mg
Impulse	• *Ingredients:* carbonated water, sucrose, taurine, glucuronolactone, caffeine, inositol, niacinimide, pyridoxine HCL, vitamin C (citric acid), vitamin B12, artificial flavors, colors • *Nutrition Facts:* serving size: 8.3 fl oz; servings per container: 1; calories: 110; fat: 0 g; sodium: 200 mg; total carbs: 28 g; sugars: 27 g; protein: 1 g; niacin: 100%; vitamin B6: 250%; vitamin B12: 80%; pantothenic acid: 50%: vitamin C: 100%
Coca Cola (for later comparison)	• *Ingredients:* carbonated water, high fructose corn syrup and/or sucrose, phosphoric acid, natural flavors, caffeine • *Nutrition Facts:* serving size: 12 fl oz; servings per container: 1; calories: 140; fat: 0 g; total carbs: 38 g; sugars: 38 g; protein: 0 g

Your Task

Research each ingredient found in these energy drinks. This information can be found in biochemistry and nutrition textbooks. Web sources may provide valuable information, but be critical in their use. Many will make unsubstantiated claims. One that can get you started for basic information is *www.chemindustry.com.* Basic information can also be garnered from *www.usda.gov/wps/portal/usda/usdahome?navid=FOOD_NUTRITION&navtype=SU*. Determine the chemical structure, the type of chemical each is, and the physiological role played by each compound. You should have sufficient information to answer Charley's list of questions as well as the additional questions listed below.

Post-Research Analysis

Using the information that your group gathered, fill out Table 11.4, placing each of the ingredients for your drink under the proper heading, and answer the questions that follow. Cite any websites that you used in your analysis.

TABLE 11.4.

Results of Your Research

Sources of Energy	Amino Acids	Stimulants and Vitamins	Other (please categorize)

Questions

1. When we say that something gives us "energy," what does that mean? What is a biological definition of energy?
2. What is the physiological role of each of the molecules in your table?
   a. Which ingredients provide energy? How do they do that?
   b. Which ingredients contribute to body repair, i.e., which help build or rebuild muscle tissue?
3. In what ways might the one(s) that does (do) not have a metabolic energy source (caffeine) provide the perception of increased energy after consumption?
4. How are the ingredients in these drinks helpful to someone expending a lot of energy, e.g., a runner?
5. Does your analysis substantiate the claim that this is an "energy drink"? If so, what molecules are the sources of energy?
6. Could your drink serve different purposes for different consumers? Explain.
7. What is the normal physiological response to increased intake of sugars? to increased intake of caffeine?
8. Is there such a thing as a "sugar high"? Explain your answer.
9. Evaluate, in terms of basic physiology and biochemistry, the statement: A lack of sleep causes a lack of energy.
10. Are the product claims legitimate? Why?
11. Should you simply buy a can of Coke rather than one of these energy drinks? Why/why not?

Assessment

Individually, or as a group, write an evaluation of the marketing claims for your drink. You may write the evaluation in the form of an article for readers of *Runner's World*. Be sure to include answers to the questions above.

Web Version

Detailed teaching notes (including a table with biochemical information for ingredients commonly found in energy drinks), the case PDF, and an answer key are available on the NCCSTS website at *sciencecases.lib.buffalo.edu/cs/collection/detail.asp?case_id=203&id=203*.

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*Page numbers printed in **boldface** type refer to figures or tables.*

SCIENCE STORIES YOU CAN COUNT ON

51 CASE STUDIES WITH QUANTITATIVE REASONING IN BIOLOGY

"Using real stories with quantitative reasoning skills enmeshed in the story line is a powerful and logical way to teach biology and show its relevance to the lives of future citizens, regardless of whether they are science specialists or laypeople."

—from the introduction to *Science Stories You Can Count On*

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