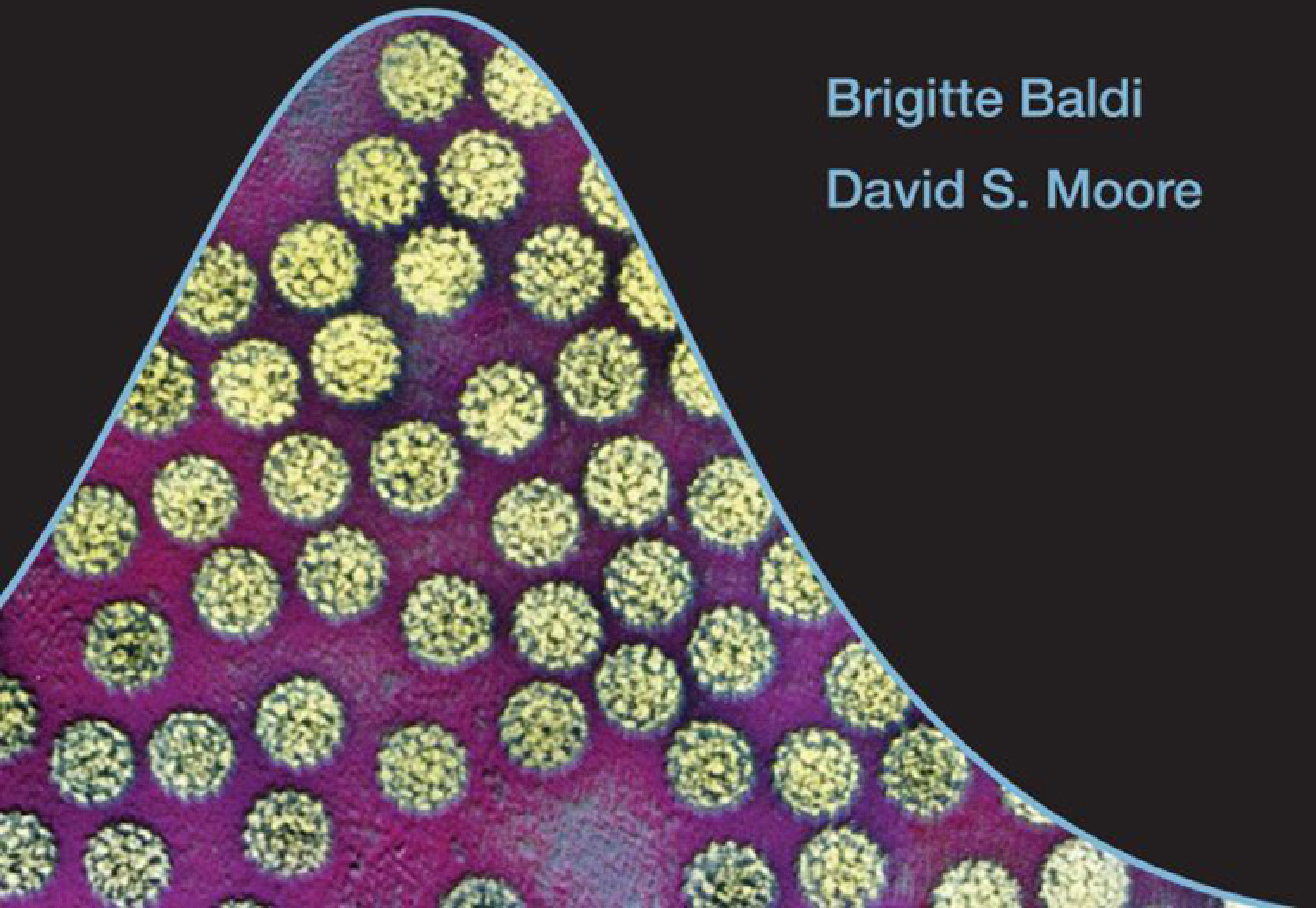
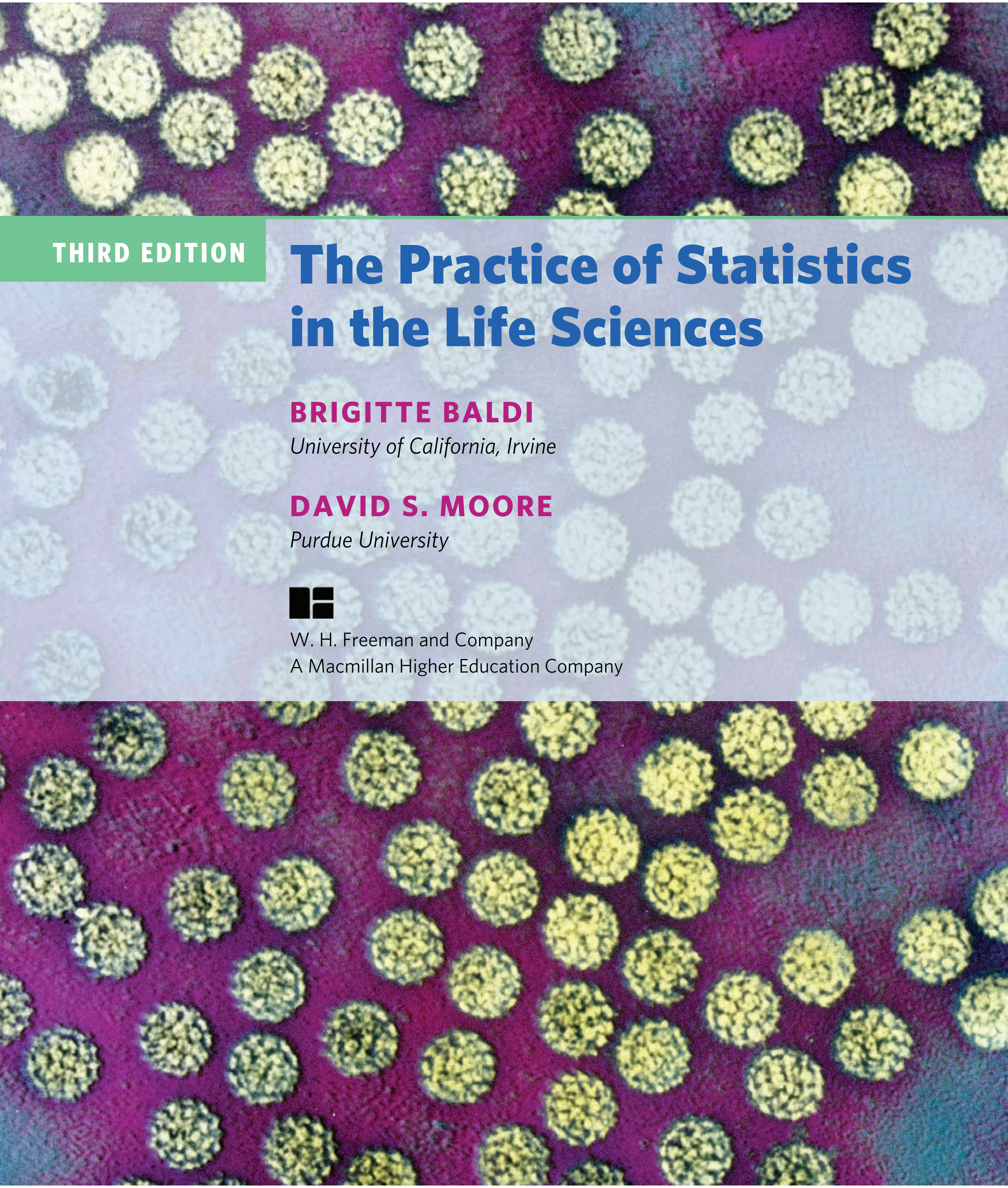
THIRD EDITION

The Practice of Statistics in the Life Sciences



Brigitte Baldi

David S. Moore



THIRD EDITION

The Practice of Statistics in the Life Sciences

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BRIEF CONTENTS

*Starred material is optional.

CONTENTS

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TO THE INSTRUCTOR: About this Book

The Practice of Statistics in the Life Sciences, third edition (*PSLS 3e*), is an introduction to statistics for college and university students interested in the quantitative analysis of life science problems. Statistics has penetrated the life sciences pervasively with a specific set of application challenges, such as observational studies with confounding variables or experiments with limited sample sizes. Consequently, students can clearly benefit from a teaching of statistics that is explicitly applied to their major. All examples and exercises in *PSLS* are drawn from diverse areas of biology, such as physiology, brain and behavior, epidemiology, health and medicine, nutrition, ecology, and microbiology. Instructors can choose to either cover a wide range of topics or select examples and exercises related to a particular field.

PSLS focuses on the applications of statistics rather than the mathematical foundation. The book is adapted from David Moore's best-selling introductory statistics textbook *The Basic Practice of Statistics* (*BPS*). *BPS* was the pioneer in presenting a modern approach to statistics in a genuinely elementary text. Like *BPS*, *PSLS* emphasizes a balanced content, working with real data, and statistical ideas. It does not require any specific mathematical skills beyond being able to read and use simple equations and can be used in conjunction with almost any level of technology for calculating and graphing.

In the following we describe in further detail for instructors the guiding principles and features of *PSLS 3e*.

GAISE guiding principles

Student audiences and access to technology have changed substantially over the years, and educational guidelines in statistics have evolved accordingly. The American Statistical Association offers a set of recommendations for introductory statistics courses at the college level described in the Guidelines for Assessment and Instruction in Statistics Education (GAISE).[1] The guiding principles of *PSLS 3e* closely follow the six GAISE recommendations for the teaching of introductory statistics.

1. **Emphasize statistical literacy and develop statistical thinking.** Students should understand the basic ideas of statistics, including the need for data, the importance of data production, the omnipresence of variability, and the quantification and explanation of variability. To this end, *PSLS* begins with data analysis (Chapters 1 to 6), then moves to data production (Chapters 7 and 8), and then to probability (Chapters 9 to 13) and inference (Chapters 14 to 28). In studying data analysis, students learn useful skills immediately and get over some of their fear of statistics. Data analysis is a necessary preliminary step to inference in practice, because inference requires suitable data. Designed data production is the surest foundation for inference, and the deliberate use of chance in random sampling and randomized comparative experiments motivates the study of probability in a course that emphasizes data-oriented statistics. *PSLS* gives a full presentation of basic probability and inference (20 of the

28 chapters) but places it in the context of statistics as a whole. Furthering this approach, each chapter contains a summary section titled "This Chapter in Context" that highlights how the concepts from the chapter relate to concepts introduced in earlier chapters and how they will figure in following chapters.

Students should also understand the general statistical approach used to solve scientific problems. A discussion box in Chapter 15 describes this approach in the context of the Nobel Prize-winning discovery of the bacterial origin of most peptic ulcers. The detailed historical and scientific account helps students see how the concepts they learn throughout the book come together to form a coherent science of data. In addition, many of the examples and exercises in *PSLS* are presented in the context of a "four-step process" (State, Plan, Solve, Conclude) intended to teach students how to work on realistic statistical problems. Figure 1 provides an overview. The process emphasizes a major theme in *PSLS:* Statistical problems originate in a real-world setting ("State") and require conclusions in the language of that setting ("Conclude"). Translating the problem into the formal language of statistics ("Plan") is a key to success. The graphs and computations needed ("Solve") are essential but are not the whole story. An icon in the margin helps students see the four-step process as a thread throughout the text. The four-step process appears whenever it fits the statistical content. Its repetitive use should foster the ability to address statistical problems independently.

2. **Use real data.** The study of statistics is supposed to help students work with data in their varied academic disciplines and later employment. This is particularly important for students in the life sciences, because they are asked to collect and analyze data in their laboratory courses and elective undergraduate research. *PSLS* prepares students by providing real (not merely realistic) data from many areas of the life sciences, with sources cited at the back of the book. Data are more than mere numbers—they are numbers with a context that should play a role in making sense of the numbers and in stating conclusions. Examples and exercises in *PSLS* give enough background to allow students to consider the meaning of their calculations.

   PSLS 3e provides about 50 examples and exercises per chapter, with both small data sets for in-class use and large data sets (with several variables and a fairly large number of subjects) more suitable for lab work or assignments. Some data sets recur throughout the book, providing an opportunity for comprehensive analysis spanning a range of statistical topics. The wealth of exercises allows instructors to emphasize some statistical topics or biological themes to tailor the content to their specific learning objectives. In addition, two discussion boxes address in greater depth some important issues when dealing with real data: The discussion box in Chapter 1 exposes students to some of the challenges of data entry and validation, while the discussion box in Chapter 2 explains how to recognize different types of outliers and how to deal with them legitimately.

ORGANIZING A STATISTICAL PROBLEM: THE FOUR-STEP PROCESS

STATE: What is the practical question, in the context of the real-world setting?
PLAN: What specific statistical operations does this problem call for?
SOLVE: Make the graphs and carry out the calculations needed for this problem.
CONCLUDE: Give your practical conclusion in the setting of the real-world problem.

CONFIDENCE INTERVALS: THE FOUR-STEP PROCESS

STATE: What is the practical question that requires estimating a parameter?

PLAN: Identify the parameter and choose a level of confidence.

SOLVE: Carry out the work in two phases:

1. **Check the conditions** for the interval you plan to use.
2. Calculate the **confidence interval** or use technology to obtain it.

CONCLUDE: Return to the practical question to describe your results in this setting.

TESTS OF SIGNIFICANCE: THE FOUR-STEP PROCESS

STATE: What is the practical question that requires a statistical test?

PLAN: Identify the parameter, state null and alternative hypotheses, and choose the type of test that fits your situation.

SOLVE: Carry out the test in three phases:

1. **Check the conditions** for the test you plan to use.
2. Calculate the **test statistic.**
3. Find the ***P*-value** using a table of Normal probabilities or technology.

CONCLUDE: Return to the practical question to describe your results in this setting.

FIGURE 1 Overview of the "four-step process" used in *PSLS 3e*.

3. **Stress conceptual understanding rather than mere knowledge of procedures.** A first course in statistics introduces many skills, from making a histogram to calculating a correlation to choosing and carrying out a significance test. In practice (even if not always in the course), calculations and graphs are automated. Moreover, anyone who makes serious use of statistics will need some specific procedures not taught in his or her college statistics course. *PSLS* therefore aims to make clear the larger patterns and big ideas of statistics in the context of learning specific skills and working with specific data. Many of the big ideas are summarized in graphical outlines in Statistics in Summary figures

within the review chapters. Review chapters also offer a comprehensive summary of the important concepts and skills that students should have mastered, along with an opportunity to select the appropriate statistical analysis without the obvious prompting from a chapter title.

Throughout the text, numerous cautionary statements are included to warn students about common confusions and misinterpretations. A handy "Caution" icon in the margin calls attention to these warnings. In addition, two discussion boxes address how a meaningful interpretation must rely on a comprehensive analysis of the data available: The discussion box in Chapter 10 discusses the interpretation of conditional probabilities in the context of diagnostic and screening tests, while the discussion box in Chapter 20 helps students assess and interpret health risks beyond the P-value of a significance test.

4. **Foster active learning in the classroom.** Learning in the classroom is the domain of the instructor. *PSLS* offers a number of opportunities to help instructors foster active learning. After a summary of the chapter's key concepts, a set of Check Your Skills multiple-choice items with answers in the back of the book lets students assess their grasp of basic ideas and skills. These problems can also be used in a "clicker" classroom response system to enable class participation.

   PSLS also provides many examples and exercises, based on small data sets or summary statistics, that can be solved during class with a simple calculator and a table or with a graphing calculator. For courses that include a computer lab component, the large data set exercises at the end of most chapters offer an opportunity for hands-on analysis with statistical software. There is no short answer given to students for these specific exercises, so that instructors can elect to assign them for a grade.

   Graphical representations of new concepts can also help students learn through experience. *PSLS* and *BPS* offer on their companion websites a set of interactive applets created to our specifications. These applets are designed primarily to help in learning statistics rather than in doing statistics. We suggest using selected applets for classroom demonstrations even if you do not ask students to work with them. The *Correlation and Regression*, *Confidence Interval*, and *P-value* applets, for example, convey core ideas more clearly than any amount of chalk and talk.

5. **Use technology for developing conceptual understanding and analyzing data.** Automating calculations increases students' ability to complete problems, reduces their frustration, and helps them concentrate on ideas and problem recognition rather than mechanics. *All students should have at least a "two-variable statistics" calculator* with functions for correlation and the least-squares regression line as well as for the mean and standard deviation. Because students have calculators, the text doesn't discuss out-of-date "computing formulas" for the sample standard deviation or the least-squares regression line.

   Many instructors will take advantage of more elaborate technology. And many students will find themselves using statistical software on the job. *PSLS* does not assume or require use of software, except in the last few chapters where the work is otherwise too tedious. *PSLS* does accommodate technology use, however, and shows students that they are gaining knowledge that will enable them to read and use output from almost any source. There are regular "Using Technology" sections throughout the text. These sections display and comment on output from different technologies, representing graphing calculators (the Texas Instruments TI-83 or TI-84), spreadsheets (Microsoft Excel), and statistical software (CrunchIt!, JMP, Minitab, R, SPSS). The output always concerns one of the main teaching examples, so that students can compare text and output.

A quite different use of technology appears in the interactive applets available on the companion website. Some examples and exercises in the text use applets, and they are marked with a dedicated icon in the margin.

6. **Use assessments to improve and evaluate student learning.** *PSLS* is structured to help students learn through practice and self-assessment. Within chapters, exercises progress from straightforward applications to comprehensive review problems, with short answers to odd-numbered exercises revealed at the back of the book. To facilitate the learning process, content is broken into digestible bites of material followed by a few Apply Your Knowledge exercises for a quick check of basic mastery. After a summary of the chapter's key concepts, a set of Check Your Skills multiple-choice items with answers in the back of the book lets students assess their grasp of basic ideas and skills (or they can be used in class in a "clicker" response system). End-of-chapter exercises integrate all aspects of the chapter. For chapters dealing with quantitative data, a set of exercises using large data sets is provided to serve as the basis for comprehensive assignments or for use within a computer lab teaching environment. Exercises in the three review chapters enlarge the statistical context beyond that of the immediate lesson. (Many instructors will find that the review chapters appear at the right points for pre-exam review.)

   PSLS 3e also comes with a new instructor test bank designed to offer more comprehensive testing options that span multiple chapters. The objective is to reinforce the idea that statistics is the science of data and that data analysis is a comprehensive approach.

What's new in the third edition?

This third edition of *PSLS* brings many new examples and exercises throughout the book, as well as opportunities to polish the exposition in ways intended to help students learn. Here are, specifically, some of the major changes:

- **New exercises and examples.** *PSLS 3e* has over 300 new or updated exercises and examples, representing nearly one-quarter of the exercises and examples in the second edition. Why such a large turnover? One reason is practical: Instructors can get bored teaching the same old material, and homework assignments need to be varied over time to avoid "recycled paper" issues. The other reason is pedagogical: Statistics *is* an exciting and relevant scientific field, and students should see this for themselves through interesting and current problems. All surveys cited in *PSLS 3e* provide the most recent data available at the time of publication, and all new problems based on research are derived from articles published in the last few years.

PSLS also strives to provide examples of statistical applications in various areas of the life sciences to accommodate different student audiences and a wide range of interests. New problems with a human focus include test performances of individuals with Highly Superior Autobiographical Memory, the relationship between body mass index and testosterone levels among adolescent males, the comparative efficiency of aerobic and resistance training for reducing body fat, and the recently approved over-the-counter OraQuick HIV test. Interesting new animal studies include the righting behavior of aphids in free fall, the paw preference of tree shrews in grasping tasks, and the effect of access to junk food on the body weights of lab rats. New plant and ecological studies include the monitoring of worldwide cases of herbicide-resistant weeds, an ecological approach to control algae bloom, and the genetics of heat resistance in rice.

- **This Chapter in Context.** Students often struggle to understand how concepts covered in different chapters are related and complementary. We created a new section in each chapter to help integrate learning across chapters. Following the Chapter Summary, a new This Chapter in Context section reminds students of the elements of previous chapters that are directly relevant to the current chapter. It also highlights how the new material will come into play in following chapters, providing a road map to guide students' learning.

  For example, this section in Chapter 24, on ANOVA, draws attention to the similarities with the one-sample and two-sample t tests from Chapters 17 and 18, as they all address inference on the parameter μ for a quantitative variable. Because of that, they share a commonality of approaches for assessing the conditions for inference, drawing on descriptive techniques from Chapter 1. Which procedure to use and what conclusions can be made depend on the study design, something discussed in Chapters 7 and 8. A reference is also made to follow-up analyses and inference for more complex designs, described in Chapter 26.

- **New discussion box.** The first two editions of *PSLS* contain a number of discussion boxes that address more leisurely and in greater depth some important conceptual issues in statistics. The third edition adds a new discussion on the challenges of data entry. Statistical consultants often lament that many problems they encounter when helping scientists stem from poor data entry choices (as well as really poor choices of design . . .). This new discussion box addresses the need for keeping detailed records of the data collection process and of all the computations performed, explains ways to organize data for easier software analysis, and describes simple methods that should be used to check for errors and missing values.

- **Tables versus technology.** We asked the *PSLS 3e* reviewers about their use of technology versus printed tables for probability and statistical computations—and found essentially an even split. Some instructors use printed tables in class because technology is not an option for exams, but others use printed tables as a pedagogical preference. Some instructors—in increasing numbers—completely forgo printed tables. Furthering changes initiated in the second edition, *PSLS 3e* uses a modular organization within the relevant chapters that offers instructors the flexibility to teach using either approach.

Why did you do that?

There is no single best way to organize the presentation of statistics to beginners. That said, our choices reflect thinking about both content and pedagogy. Here are comments on several "frequently asked questions" about the order and selection of material in *PSLS 3e*.

Why does the distinction between population and sample not appear in Part I? The concepts of populations and samples are briefly introduced in Chapter 1, but the distinction between them is not emphasized until much later in the book. This is a sign that there is more to statistics than inference. In fact, statistical inference is appropriate only in rather special circumstances. The chapters in Part I present tools and tactics for describing data—any data. Many data sets in these chapters do not lend themselves to inference, because they represent an entire population. John Tukey of Bell Labs and Princeton, the philosopher of modern data analysis, insisted that the population-sample distinction be avoided when it is not relevant, and we agree with him.

Why not begin with data production? It is certainly reasonable to do so—the natural flow of a planned study is from design to data analysis to inference. But in their future employment most students will use statistics mainly in settings other than planned research studies. We place the design of data production (Chapters 7 and 8) after data analysis to emphasize that data-analytic techniques apply to any data. One of the primary purposes of statistical designs for producing data is to make inference possible, so the discussion in Chapters 7 and 8 opens Part II and motivates the study of probability.

Why not delay correlation and regression until late in the course, as is traditional? *PSLS 3e* begins by offering experience working with data and gives a conceptual structure for this nonmathematical but essential part of statistics. Students profit from more experience with data and from seeing the conceptual structure worked out in relations among variables as well as in describing single-variable data. Correlation and least-squares regression are very important descriptive tools, and they are often used in settings where there is no population-sample distinction, such as studies based on state records or average species data. Perhaps most important, the *PSLS* approach asks students to think about what kind of relationship lies behind the data (confounding, lurking variables, association doesn't imply causation, and so on), without overwhelming them with the demands of formal inference methods. Inference in the correlation and regression setting is a bit complex, demands software and a close examination of residuals, and often comes right at the end of the course. Delaying all mention of correlation and regression to that point often impedes the mastering of basic uses and properties of these methods. We consider Chapters 3 and 4 (correlation and regression) essential and Chapter 23 (regression inference and residual plots) optional when time constraints limit the amount of material that can be taught. For similar reasons, two-way tables are introduced first in the context of exploratory data analysis before moving on to inference with the chi-square test in Part III.

What about probability? Chapters 9, 11, and 13 present in a simple format the ideas of probability and sampling distributions that are needed to understand inference. These chapters go from the idea of probability as long-term regularity through concrete ways of assigning probabilities to the idea of the sampling distribution of a statistic. The central limit theorem appears in the context of discussing the sampling distribution of a sample mean. What is left with the *optional* Chapters 10 and 12 is mostly "general probability rules" (including conditional probability) and the binomial and Poisson distributions.

We suggest that you omit these optional chapters unless they represent important concepts for your particular audience. Experienced teachers recognize that students find probability difficult, and research has shown that this is true even for professionals. If a course is intended for med or premed students, for instance, the concept of conditional probability is very relevant because it is a key part of diagnosis that both doctors and patients have difficulty interpreting.[2] However, attempting to present a substantial introduction to probability in a data-oriented statistics course for students who are not mathematically trained is a very difficult challenge. Instructors should keep in mind that formal probability does not help students master the ideas of inference as much as we teachers often imagine, and it depletes reserves of mental energy that might better be applied to essential statistical ideas.

Why use the *z* procedures for a population mean to introduce the reasoning of inference? This is a pedagogical issue, not a question of statistics in practice. Some time in the golden future, we will start with resampling methods, as permutation tests make the reasoning of tests clearer than any traditional approach. For now, the main choices are z for a mean and z for a proportion.

The z procedures for means are pedagogically more accessible to students. We can say up front that we are going to explore the reasoning of inference in an overly simple setting. Remember, exactly Normal populations and true simple random samples are as unrealistic as known σ, especially in the life sciences. All the issues of practice—robustness against lack of Normality and application when the data aren't an SRS, as well as the need to estimate σ—are put off until, with the reasoning in hand, we discuss the practically useful t procedures. This separation of initial reasoning from messier practice works well.

On the contrary, starting with inference for p introduces many side issues: no exact Normal sampling distribution, but a Normal approximation to a discrete distribution; use of $\hat{p}$ in both the numerator and the denominator of the test statistic to estimate both the parameter p and $\hat{p}$'s own standard deviation; loss of the direct link between test and confidence interval. In addition, we now know that the traditional z confidence interval for p is often grossly inaccurate, as explained in the following section. Lastly, major polling organizations like Gallup and Pew now report substantially different margins of error (likely accounting for data weighing), making it increasingly challenging to show students real-life applications of the z method for a proportion.

Why does the presentation of inference for proportions go beyond the traditional methods? Recent computational and theoretical work has demonstrated convincingly that the standard confidence intervals for proportions can be trusted only for very large sample sizes. It is hard to abandon old friends, but the graphs in section 2 of the paper by Brown, Cai, and DasGupta in the May 2001 issue of *Statistical Science* are both distressing and persuasive.[3] The standard intervals often have a true confidence level much less than what was requested, and requiring larger samples encounters a maze of "lucky" and "unlucky" sample sizes until very large samples are reached. Fortunately, there is a simple cure: Just add two successes and two failures to your data. (Therefore, no additional software tool is required for this procedure.) We present these "plus four intervals" in Chapters 19 and 20, along with guidelines for use.

Why didn't you cover Topic X? Introductory texts ought not to be encyclopedic. Including each reader's favorite special topic results in a text that is formidable in size and intimidating to students. The topics covered in *PSLS* were chosen because they are the most commonly used in the life sciences and they are suitable vehicles for learning broader statistical ideas. Three chapters available on the companion website cover more advanced inference procedures. Students who have completed the core of *PSLS* will have little difficulty moving on to more elaborate methods.

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Brigitte Baldi and David S. Moore

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CrunchIT!® is a web-based statistical program that allows users to perform all the statistical operations and graphing needed for an introductory statistics course and more. It saves users time by automatically loading data from *PSLS3e*, and it provides the flexibility to edit and import additional data.

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EESEE Case Studies (Electronic Encyclopedia of Statistical Examples and Exercises), developed by The Ohio State University Statistics Department, teach students to apply their statistical skills by exploring actual case studies using real data.

Data files are available in ASCII, Excel, TI, Minitab, SPSS (an IBM Company),[1] and JMP formats.

Student Solutions Manual provides solutions to the odd-numbered exercises in the text. Available electronically within LaunchPad, as well as in print form.

Interactive Table Reader allows students to use statistical tables interactively to seek the information they need.

[1] SPSS was acquired by IBM in October 2009.

Instructor's Guide with Solutions includes teaching suggestions, chapter comments, and detailed solutions to all exercises. Available electronically within LaunchPad, as well as on the IRCD and in print form.

Test Bank offers hundreds of multiple-choice questions. Also available on CD-ROM (for Windows and Mac), where questions can be downloaded, edited, and resequenced to suit each instructor's needs.

Lecture PowerPoint Slides offer a detailed lecture presentation of statistical concepts covered in each chapter of *PSLS*.

Additional Resources Available with PSLS3e

Companion Website `www.whfreeman.com/psls3e` This open-access website includes statistical applets, data files, and self-quizzes. The website also offers three optional companion chapters covering ANOVA, nonparametric tests, and multiple and logistic regression.

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TO THE STUDENT: Statistical Thinking

Statistics is about data. Data are numbers, but they are not "just numbers." **Data are numbers with a context.** The number 10.5, for example, carries no information by itself. But a newborn weighing 10.5 pounds is an indication of a healthy size at birth. The context engages our background knowledge and allows us to make judgments; it makes the number informative.

Statistics is the science of data. To gain insight from data, we make graphs and do calculations. But graphs and calculations are guided by ways of thinking that amount to educated common sense. Let's begin our study of statistics with an informal look at some principles of statistical thinking.

DATA BEAT ANECDOTES

An anecdote is a striking story that sticks in our minds exactly because it is striking. Anecdotes humanize an issue, but they can be misleading.

Does living near power lines cause leukemia in children? The National Cancer Institute spent 5 years and $5 million gathering data on this question. The researchers compared 638 children who had leukemia with 620 who did not. They went into the homes and measured the magnetic fields in the children's bedrooms, in other rooms, and at the front door. They recorded facts about power lines near the family home and also near the mother's residence when she was pregnant. Result: no connection between leukemia and exposure to magnetic fields of the kind produced by power lines. The editorial that accompanied the study report in the *New England Journal of Medicine* thundered, "It is time to stop wasting our research resources" on the question.[1]

Now compare the effectiveness of a television news report of a 5-year, $5 million investigation against a televised interview with an articulate mother whose child has leukemia and who happens to live near a power line. In the public mind, the anecdote wins every time. A statistically literate person knows better. **Data are more reliable than anecdotes, because they systematically describe an overall picture rather than focus on a few incidents.**

WHERE THE DATA COME FROM IS IMPORTANT

The advice columnist Ann Landers once asked her readers, "If you had it to do over again, would you have children?" A few weeks later, her column was headlined "70% OF PARENTS SAY KIDS NOT WORTH IT." Indeed, 70% of the nearly 10,000 parents who wrote in said they would not have children if they could make the choice again. *Do you believe that 70% of all parents regret having children?*

You shouldn't. The people who took the trouble to write Ann Landers are not representative of all parents. Their letters showed that many of them were angry at their children. All we know from these data is that there are some unhappy parents out there. A statistically designed poll, unlike Ann Landers's appeal, targets specific people chosen in a way that gives all parents the same chance to be asked. Such a poll showed that 91% of parents *would* have children again. Where data come from matters a lot. If you are careless about how you get your data, you may announce 70% "no" when the truth is about 90% "yes."

Here's another question: *Should episiotomy be a routine part of childbirth?* Episiotomy is the surgical cut of the skin and muscles between the vagina and the rectum sometimes performed during childbirth. Until recently, it was one of the most common surgical procedures in women in the United States, performed routinely to speed up childbirth and in the hope that it would help prevent tearing of the mother's tissue and possible later incontinence. Episiotomy rates vary widely by hospital and by physician, based principally on personal beliefs about the procedure's benefits.

However, recent clinical trials and epidemiological studies have shown no benefit of episiotomy unless the baby's health requires accelerated delivery or a large natural tearing seems likely. In fact, these studies indicate that episiotomy is associated with longer healing times and increased rates of complications, including infection, extensive tearing, pain, and incontinence.[2]

To get convincing evidence on the benefits and risks of episiotomy, we need unbiased data. Proper clinical trials and epidemiological studies rely on randomness of patient or treatment selection to avoid bias. The careful studies of the risks and benefits of routine episiotomy could be trusted because they had sound data collection designs. As a result, rates of episiotomy in the United States have dropped substantially.

The most important information about any statistical study is how the data were produced. Only statistically designed opinion polls and surveys can be trusted. Only experiments can give convincing evidence that an alleged cause really does account for an observed effect.

BEWARE THE LURKING VARIABLE

Energy drinks contain high levels of caffeine, which we know can temporarily boost alertness but can also cause sleep problems later on. A survey of U.S. service members in a combat environment in Afghanistan showed that those consuming energy drinks three or more times a day slept less, had more sleep disruptions, and were more likely to fall asleep on duty than those consuming fewer or no energy drinks.[3] What shall we make of this finding? Among servicemen in combat deployment, does the frequent consumption of energy drinks impair sleep or do individuals with impaired sleep consume more energy drinks to stay alert on the job? The answer may well be both, in a self-reinforcing loop. It is also possible that other factors, such as high stress, both interfere with sleep and create a desire for heightened alertness from energy drinks. A statistician knows that a causal link cannot be established here, because the data from this survey are simply observations.

Should women take hormones such as estrogen after menopause, when natural production of these hormones ends? In 1992, several major medical organizations said "yes." In particular, women who took hormones seemed to reduce their risk of a heart attack by 35% to 50%. But in 2002, the National Institutes of Health declared these findings wrong. Use of hormones after menopause immediately plummeted. Both recommendations were based on extensive studies. What happened?

The evidence in favor of hormone replacement came from a number of *observational studies* that compared women who were taking hormones with others who were not. But women who choose to take hormones are very different from women who do not: They are richer and better educated and see doctors more often. These women do many things to maintain their health. It isn't surprising that they have fewer heart attacks.

We can't conclude that hormone replacement reduces heart attacks just because we see a relationship in the data. Education and affluence are *lurking variables*, background factors that help explain the relationship between hormone replacement and good health.

Almost all relationships between two variables are influenced by other variables lurking in the background. To understand the relationship between two variables, you must often look at other variables. Careful statistical studies try to think of and measure possible lurking variables in order to correct for their influence. As the hormone saga illustrates, this is not always done. News reports often ignore possible lurking variables that might ruin a good headline. The habit of asking "What might lie behind this relationship?" is part of thinking statistically.

Another way to address the effect of lurking variables is by designing careful *experiments*. Several experiments randomly assigned volunteer women either to hormone replacement or to dummy pills that looked and tasted the same as the hormone pills. By 2002, these experiments agreed that hormone replacement does *not* reduce the risk of heart attacks, at least for older women. Faced with this better evidence, medical authorities changed their recommendations.[4]

ALWAYS LOOK AT THE DATA

Yogi Berra said it: "You can observe a lot by just watching." That's a motto for learning from data. **A few carefully chosen graphs are often more instructive than great piles of numbers.**

Let's look at some data. Figure 1 displays a histogram of the body lengths of 56 perch (*Perca fluviatilis*) caught in a Finnish lake.[5] Each bar in the graph represents how many perch had a body length between two values on the horizontal axis. For example, the tallest bar indicates that 17 perch had a body length between 20 and 25 centimeters (cm).

We see great variability in perch body lengths, from about 5 to 50 cm, but we also notice two clear clusters: One group of smaller fish and one group of larger fish. This suggests that the data include two different groups of perch, possibly males

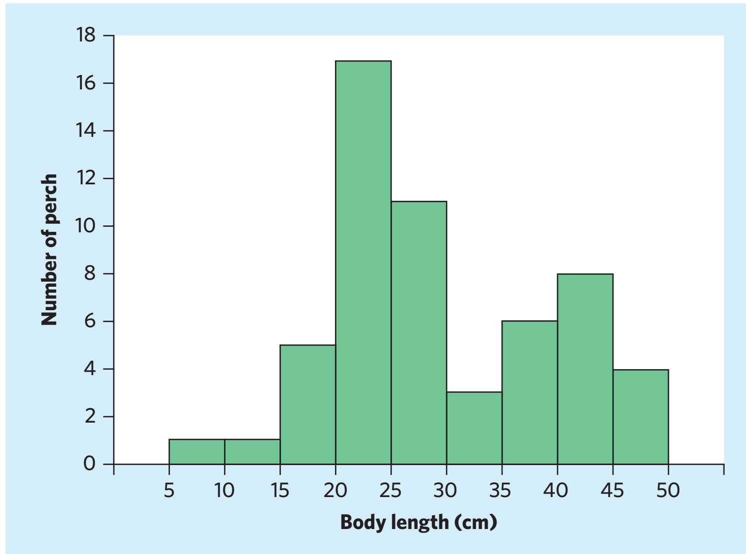

FIGURE 1 Body lengths of 56 perch from a Finnish lake. Always look at the data: Two separate clusters are clearly visible.

and females or perch of different ages. In fact, observations in the wild indicate that perch can become much larger if they survive to a very old age (up to 22 years).

Any attempt to summarize the data in Figure 1 without a close inspection first would miss the two distinct clusters. Failure to examine any data carefully can lead to misleading or absurd results. As humorist Des McHale put it, "The average human has one breast and one testicle."

VARIATION IS EVERYWHERE

Many students in biology lab courses are surprised to obtain somewhat different results when they repeat an experiment. Yet, variability is ubiquitous.

Figure 2 plots the ventilation rates of seven goldfish placed in tanks of varying temperature.[6] Each goldfish is represented by one color. While there is a clear overall pattern in this figure, there is also a lot of variability, with ventilation rates ranging overall from 6 to 119 opercular movements per minute. Some of that variability can be attributed to lack of precision in measurements, some to fish physiology, and some to slight differences in circumstances at the time of each measurement (such as movements around the fish tanks that might stress the fish). Before the experiment, the fish were kept in tanks set to 22 degrees Celsius. At that temperature, the fish ventilation rates range from about 60 to 100 opercular movements per minute. Yet when the same seven fish are transferred to containers with warmer water, their ventilation rates increase overall. And when the fish are transferred to containers at lower temperatures, the ventilation rates decrease quite dramatically. These data show that ventilation rate in goldfish varies both from fish to fish and as a function of water temperature.

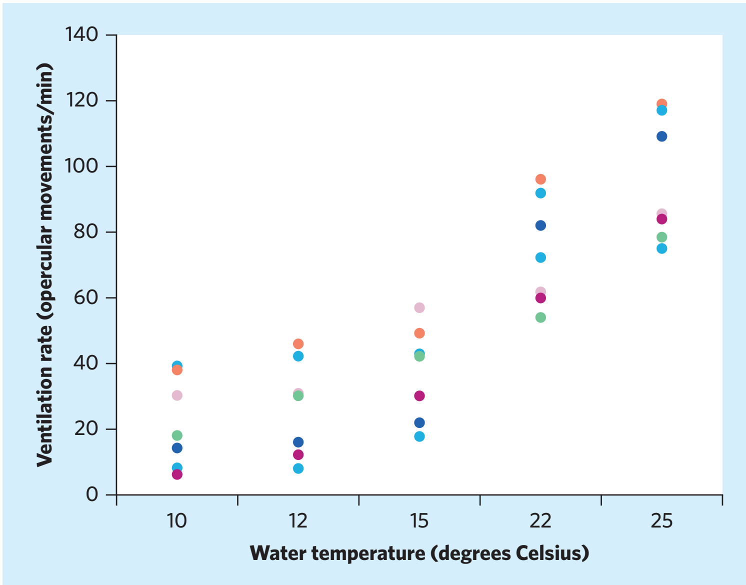

FIGURE 2 Variation is everywhere: the ventilation rates of seven goldfish placed in tanks with varying water temperature.

Students are not the only ones with a tendency to underestimate variability in real data. Here is Arthur Nielsen, head of the country's largest market research firm, describing his experience:

> *Too many business people assign equal validity to all numbers printed on paper. They accept numbers as representing Truth and find it difficult to work with the concept of probability. They do not see a number as a kind of shorthand for a range that describes our actual knowledge of the underlying condition.*[7]

Variation is everywhere. Individuals vary; repeated measurements on the same individual vary; almost everything varies over time. One reason we need to know some statistics is that statistics helps us deal with variation.

CONCLUSIONS ARE NOT CERTAIN

Most women who reach middle age have regular mammograms to detect breast cancer. *Do mammograms reduce the risk of dying of breast cancer?* Doctors rely on clinical trials that compare different ways of screening for breast cancer. The conclusion of the U. S. Preventive Services Task Force after examining all the data available is that biennial mammograms reduce the risk of death in women aged 50 to 69 years by about 16.5% compared with no screening.[8]

Because variation is everywhere, conclusions are uncertain. Statistics gives us a language for talking about uncertainty that is used and understood by statistically literate people everywhere. On average, women who have mammograms every two years between the ages of 50 and 69 are less likely to die of breast cancer. But because variation is everywhere, the results are different for different women. Some women who have biennial mammograms die of breast cancer, and some who never have mammograms live long, breast-cancer-free lives. Statistical conclusions are "on average" statements only. In addition, the conclusion that mammograms reduce the risk of death from breast cancer comes from experiments involving some, and not all, women aged 50 to 69 years. In fact, the various studies found a reduction in breast cancer deaths versus no screening ranging from 15% to 23%. Well then, can we be certain that mammograms reduce risk on average? No. We can be very confident, but we can't be certain. We will learn how to quantify our level of confidence in statistical conclusions.

Statistical Thinking and You

What Lies Ahead in This Book The purpose of *The Practice of Statistics in the Life Sciences* (*PSLS*), third edition, is to give you a working knowledge of the ideas and tools of practical statistics. We will divide practical statistics into four main areas:

1. **Data analysis** concerns methods and strategies for exploring, organizing, and describing data using graphs and numerical summaries. Only organized data can illuminate reality. Only thoughtful exploration of data can defeat the lurking variable. Part I of *PSLS* (Chapters 1 to 6) discusses data analysis.
2. **Data production** provides methods for producing data that can give clear answers to specific questions. Where the data come from really is important. Basic concepts about how to select samples and design experiments are the most influential ideas in statistics. These concepts are the subject of Chapters 7 and 8.
3. **Probability** is the language that describes variation and uncertainty. Because we are concerned with practice rather than theory, we need only a limited knowledge of probability. Chapters 9, 11, and 13 introduce us to the most important probability rules and models. Chapters 10 and 12 offer more probability for those who want it.
4. **Statistical inference** moves beyond the data in hand to draw conclusions about some wider universe, taking into account that variation is everywhere and that conclusions are uncertain. Chapters 14 and 15 discuss the reasoning of statistical inference. These chapters are the key to the rest of the book. Chapters 17 to 21 present inference as used in practice in the most common settings. Chapters 22 to 24, and the Optional Companion Chapters 26 to 28 on the companion website, concern more advanced or specialized kinds of inference.

Statistics, however, is an integrated science of data, and you will see that concepts from one area often relate directly to concepts from other areas. To help you see this, each chapter contains a summary section titled This Chapter in Context. These sections highlight how the concepts from the current chapter relate to concepts introduced in earlier chapters and how they will figure in following chapters.

Because data are numbers with a context, doing statistics means more than manipulating numbers. You must **state** a problem in its real-world context, **plan** your specific statistical work in detail, **solve** the problem by making the necessary graphs and calculations, and **conclude** in context by explaining what your findings say about the real-world setting. We'll make regular use of this four-step process to encourage good habits that go beyond graphs and calculations to ask, "What do the data tell me?"

4 STEP

Statistics does involve lots of calculating and graphing. The text presents the techniques you need, but you should use a calculator or software to automate calculations and graphs as much as possible. Because the big ideas of statistics don't depend on any particular level of access to computing, *PSLS* does not require software. Even if you make little use of technology, you should look at the Using Technology sections throughout the book. You will see at once that you can read and use the output from almost any technology used for statistical calculations. The ideas really are more important than the details of how to do the calculations.

Unless you have constant access to software or a graphing calculator, *you will need a calculator with some built-in statistical functions*. Specifically, your calculator should find means and standard deviations and calculate correlations and regression lines. Look for a calculator that claims to do "two-variable statistics" or mentions "regression." You will get the most, though, out of a graphing calculator or statistical software.

Because graphing and calculating are automated in statistical practice, the most important assets you can gain from the study of statistics are an understanding of the big ideas and the beginnings of good judgment in working with data. *PSLS* aims to explain the most important ideas of statistics, not just teach methods. Some examples of big ideas that you will see are "always plot your data," "randomized comparative experiments," and "statistical significance." Some particularly important ideas (such as how to treat outliers and the scientific approach) are given more extensive treatment with real-life examples in discussions placed throughout the book.

You learn statistics by doing statistical problems. As you read, you will see several levels of exercises, arranged to help you learn. Short Apply Your Knowledge problem sets appear after each major idea. These are straightforward exercises that help you solidify the main points as you read. Be sure you can do these exercises before going on. The end-of-chapter exercises begin with multiple-choice Check Your Skills exercises (with all answers in the back of the book). Use them to check your grasp of the basics. The regular Chapter Exercises help you combine all the ideas of a chapter. At the end of chapters that deal with the analysis of quantitative data, you will find additional exercises marked with the "Large data set" icon; these provide an opportunity to apply your statistical skills to the kind of large and complex data sets encountered very often in the life sciences. Finally, the three Part Review chapters look back over major blocks of learning, with many review exercises. At each step, you are given less advance knowledge of exactly what

LARGE DATA SET

statistical ideas and skills the problems will require, so each type of exercise requires more understanding.

The Part Review chapters (and the individual optional chapters on the companion website) include point-by-point lists of specific things you should be able to do. Go through that list, and be sure you can say "I can do that" to each item. Then try some of the review exercises. Every odd-numbered exercise in the book (except for exercises marked "Large data set") has a short answer available at the back of the book (or on the companion website for optional chapters). You can use this to check your work.

The key to learning is persistence. The main ideas of statistics, like the main ideas of any important subject, took a long time to discover and take some time to master. The gain will be worth the pain.

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Brigitte Baldi is a graduate of France's Ecole Normale Supérieure in Paris. In her academic studies, she combined a love of math and quantitative analysis with wide interests in the life sciences. She majored in math and biology and obtained a master's in molecular biology and biochemistry and a master's in cognitive sciences. She earned her PhD in neuroscience from the Université Paris VI, studying multisensory integration in the brain; and as a postdoctoral fellow at the California Institute of Technology, she used computer simulations to study patterns of brain reorganization after lesion. She then worked as a management consultant advising corporations before returning to academia to teach statistics.

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In recent years, Professor Moore has devoted his attention to the teaching of statistics. He was the content developer for the Annenberg/Corporation for Public Broadcasting college-level telecourse *Against All Odds: Inside Statistics* and for the series of video modules *Statistics: Decisions through Data,* intended to aid the teaching of statistics in schools. He is the author of influential articles on statistics education and of several leading texts. Professor Moore has served as president of the International Association for Statistical Education and has received the Mathematical Association of America's national award for distinguished college or university teaching of mathematics.