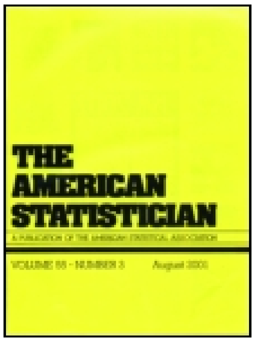

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Teaching the Next Generation of Statistics Students to "Think With Data": Special Issue on Statistics and the Undergraduate Curriculum

Nicholas J. HORTON and Johanna S. HARDIN

This is an exciting time to be a statistician. The contribution of the discipline of statistics to scientific knowledge is widely recognized (McNutt 2014) with increasingly positive public perception. Many feel "daunted by the challenge of extracting understanding from floods of disconnected data that threaten to swamp every discipline" (Yamamoto 2013).

Demand for statisticians is strong, and as such, 'statistician' frequently ranks as a top job (Wasserstein 2015). The McKinsey report (Manyika et al. 2011) makes clear the need for new graduates with "deep analytical skills," and many (most?) of these new workers will be trained at the undergraduate level. Fortunately, the recent growth of undergraduate statistics programs is impressive. While still small in absolute numbers they have nearly doubled between 2010 and 2013 (Wasserstein 2015) and are on track to continue to increase.

But there are challenges as well as opportunities in this new world of data (Horton 2015; Ridgway 2015a). The traditional statistics curriculum with mathematical foundations has not kept up with pressing demands for students who can make sense of data. Calls for transformed undergraduate education have resonated nationally (Holdren and Lander 2012; Zorn et al. 2014). These pressures led ASA President Nathaniel Schenker to convene an ASA workgroup to update the association's guidelines for undergraduate programs. The group, with broad representation from academia, industry, and government, put forward guidelines that were endorsed by the ASA Board of Directors in November 2014 (ASA 2014). Table 1 includes the full executive summary (a copy of the guidelines and related resources can be found at http://www.amstat.org/education/curriculumguidelines.cfm).

Much of the statistics education literature focuses on the introductory statistics course and statistics before college. Given the relatively few decades since the establishment of undergraduate statistics programs, this is not surprising. While there has been impressive growth in the number of students taking introductory statistics, there has been a relative dearth of articles on the curriculum beyond the introductory course. The 2014 ASA curriculum guidelines focus particular attention on the relationships between courses and student experiences beyond what has been implemented in traditional lecture courses. This issue of *The American Statistician* includes a set of articles that addresses the challenges and opportunities for undergraduate programs in statistics.

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Many aspects of the revised guidelines are not new. As an example, consider the preface of the 1992 Committee on Applied and Theoretical Statistics (CATS) workshop on "Modern Interdisciplinary University Statistics Education" that touches on a number of key aspects from the 2014 ASA guidelines (including graphics, communications, and applications) CATS (1994):

> At its August 1992 meeting in Boston, the Committee on Applied and Theoretical Statistics (CATS) noted widespread sentiment in the statistical community that upper-level undergraduate and graduate curricula for statistics majors are currently structured in ways that do not provide sufficient exposure to modern statistical analysis, computational and graphical tools, communication skills, and the ever growing interdisciplinary uses of statistics. Approaches and materials once considered standard are being rethought. The growth that statistics has undergone is often not reflected in the education that future statisticians receive. There is a need to incorporate more meaningfully into the curriculum the computational and graphical tools that are today so important to many professional statisticians. There is a need for improved training of statistics students in written and oral communication skills, which are crucial for effective interaction with scientists and policy makers. More realistic experience is needed in various application areas for which statistics is now a key to further progress. (CATS 1994, vii)

We heartily concur. We also agree with Jon Kettenring's advice (CATS 1994, 5–9) that "Industry needs holistic statisticians who are nimble problem solvers." The idea that an undergraduate statistics major develops general problem solving skills to use data to make sense of the world is powerful. We are concerned that many of our graduates do not have sufficient skills to be effective in the modern workforce. Thomas Lumley (personal communication, 2015) has stated that our students know how to deal with $n \to \infty$, but cannot deal with a million observations. If statistics is the science of learning from data, then our students need to be able to "think with data" (as Diane Lambert of Google has so elegantly described).

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Table 1. Executive Summary—ASA Guidelines for Undergraduate Programs in Statistical Science (endorsed by the Board of Directors, November 2014)

Executive Summary. The American Statistical Association endorses the value of undergraduate programs in statistics as a reflection of the increasing importance of the discipline. We expect statistics programs to provide sufficient background in the following core skill areas: statistical methods and theory, data management, computation, mathematical foundations, and statistical practice. Statistics programs should be flexible enough to prepare bachelor's graduates to either be functioning statisticians or go on to graduate school.

The widely cited McKinsey report states that "by 2018, the United States alone could face a shortage of 140,000 to 190,000 people with deep analytical skills as well as 1.5 million managers and analysts with the know-how to use the analysis of big data to make effective decisions" (Manyika et al. 2011). A large number of those will be at the bachelor's level. The number of bachelor's graduates in statistics has increased by more than 140% since 2003 (21% from 2012 to 2013).

Much has changed since the previous guidelines were disseminated in 2000. The 2014 guidelines reflect changes in curriculum and suggested pedagogy. Institutions need to ensure that students entering the workforce or heading to graduate school have the appropriate capacity to "think with data" and to pose and answer statistical questions.

Key points include:

Increased importance of data science: Working with data requires extensive computing skills. To be prepared for statistics and data science careers, students need facility with professional statistical analysis software, the ability to access and manipulate data in various ways, and the ability to perform algorithmic problem-solving. In addition to more traditional mathematical and statistical skills, students should be fluent in higher-level programming languages and facile with database systems.

Real applications: Data should be a major component of statistics courses. Programs should emphasize concepts and approaches for working with complex data and provide experiences in designing studies and analyzing nontextbook data.

More diverse models and approaches: Students require exposure to and practice with a variety of predictive and explanatory models in addition to methods for model building and assessment. They must be able to understand issues of design, confounding, and bias. They need to be know how to apply their knowledge of theoretical foundations to the sound analysis of data.

Ability to communicate: Students need to be able to communicate complex statistical methods in basic terms to managers and other audiences and to visualize results in an accessible manner. They must have a clear understanding of ethical standards. Programs should provide multiple opportunities to practice and refine these statistical practice skills.

These guidelines are intended to be flexible while ensuring that programs provide students with the appropriate background along with necessary critical thinking and problem-solving skills to thrive in our increasingly data-centric world. Programs are encouraged to be creative with their curriculum to provide a synthesis of theory, methods, computation, and applications.

Likely the first and most important place to start the curricular conversation is with the courses that follow an introductory statistics course. For many years, the "second course" has often been thought to be synonymous with regression. But even in 2000, Tarpey encouraged thinking outside the box for the applied regression and theoretical statistics courses:

Table 2. Key articles on statistics in the undergraduate curriculum (* denotes in this issue)

Overview	
Pierie (1986)	Guidelines for Bachelor Degree Curricula in Statistics: An Interim Report
Moore et al. (1995)	Statistics Education Fin De Siècle
Wild and Pfannkuch (1999)	Statistical Thinking in Empirical Enquiry
Tarpey et al. (2000)	Curriculum Guidelines for Bachelor of Arts Degrees in Statistical Science
Bryce et al. (2000)	Curriculum Guidelines for Bachelor of Science Degrees in Statistical Science
Breiman (2001)	Statistical Modeling: The Two Cultures
Moore (2001)	Undergraduate Programs and the Future of Academic Statistics
Ritter, Starbuck, and Hogg (2001)	Advice From Prospective Employers on Training BS Statisticians
Cannon et al. (2002)	Guidelines for Undergraduate Minors and Concentrations in Statistical Science
Scheaffer and Stasny (2004)	The State of Undergraduate Education in Statistics: A Report From the CBMS 2000
DeVeaux and Velleman (2008)	Math is Music: Statistics is Literature
Brown and Kass (2009)	What is Statistics?
Nolan and Temple Lang (2010)	Computing in the Statistics Curriculum
Blair, Kirkman, and Maxwell (2010)	Statistical Abstract of Undergraduate Programs in the Mathematical Sciences in the United States: Fall 2010 CBMS Survey
Cobb (2011)	Teaching Statistics: Some Important Tensions
Bailer et al. (2012)	Report on the ASA Workgroup on Master's Degrees
Johnstone (2014)	Where are the Majors?
Utts (2015a)	The Many Facets of Statistics Education: 175 Years of Common Themes
Horton (2015)	Challenges and Opportunities for Statistics and Statistical Education: Looking Back, Looking Forward
Wild (2015a)	On Locating Statistics in the World of Finding Out
Saxe et al. (2015)	A Common Vision for Undergraduate Mathematical Science Programs in 2025
ASA (2015)	The Statistical Education of Teachers
Cobb (2015a)*	Mere Renovation is Too Little Too Late: We Need to Rethink Our Undergraduate Curriculum from the Ground Up

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Table 2. Key articles on statistics in the undergraduate curriculum (* denotes in this issue) *(continued)*

Computation and algorithmic thinking	
CATS (1994)	Modern Interdisciplinary University Statistics Education
Biehler (1997)	Software for Learning and for Doing Statistics
Zhu et al. (2013)	Data Acquisition and Preprocessing in Studies on Humans: What is Not Taught in Statistics Classes?
Wickham (2014)	Tidy Data
Horton et al. (2015)	Setting the Stage for Data Science: Integration of Data Management Skills in Introductory and Second Courses in Statistics
Chamandy, Muralidharan, and Wager (2015)*	Teaching Statistics at Google-Scale
Data science	
Cleveland (2001)	Data Science: An Action Plan for Expanding the Technical Areas of the Field of Statistics
Finzer (2013)	The Data Science Education Dilemma
Spiegelhalter (2014)	The Future Lies in Uncertainty
Harville (2014)	The Need for More Emphasis on Prediction: A "nondenominational" Model-Based Approach
Madigan and Wasserstein (2014)	Statistics and Science: A Report of the London Workshop on the Future of the Statistical Sciences
Ridgway (2015a)	Implications of the Data Revolution for Statistics Education
Nolan and Temple Lang (2015b)	Data Science in R: A Case Studies Approach to Computational Reasoning and Problem Solving
Baumer (2015)*	A Data Science Course for Undergraduates: Thinking with Data
Hardin et al. (2015)*	Data Science in Statistics Curricula: Preparing Students to "Think with Data"
Khachatryan (2015)*	Incorporating Statistical Consulting Case Studies in Introductory Time Series Courses
Leman, House, and Hoegh (2015)*	Developing a New Interdisciplinary Computational Analytics Undergraduate Program: A Qualitative-Quantitative-Qualitative Approach
Visualization and multivariate thinking	
Friendly (2008)	The Golden Age of Statistical Graphics
Nolan and Temple Lang (2009)	Approaches to Broadening the Statistics Curricula
Gould (2010)	Statistics and The Modern Student
Grolemund and Wickham (2014)	A Cognitive Interpretation of Data Analysis
Nolan and Perrett (2015)	Teaching and Learning Data Visualization: Ideas and Assignments
Wagaman (2015)	Meeting Student Needs for Multivariate Data Analysis: A Case Study in Teaching a Multivariate Data Analysis Course With no Prerequisites
Second courses	
Mosteller and Tukey (1977)	Data Analysis and Regression: A Second Course
Fecso et al. (1996)	Teaching Survey Sampling
Kolenikov (2015)	Training for The Modern Survey Statistician
Blades, Schaalje, and Christensen (2015)*	The Second Course in Statistics: Design and Analysis of Experiments?
Grimshaw (2015)*	A Framework for Infusing Authentic Data Experiences Within Statistics Courses
Kuiper and Sturdivant (2015)*	Using Online Game-Based Simulations to Strengthen Students' Understanding of Practical Statistical Issues in Real-World Data Analysis
Assessment	
Hogg (1999)	Let's use CQI in our Statistics Programs
Garfield (1994)	Beyond Testing and Grading: Using Assessment to Improve Student Learning
Garfield et al. (2011)	Rethinking Assessment of Student Learning in Statistics Courses
ASA (2005)	Guidelines for Assessment and Instruction in Statistics Education College Report
Starnes (2015)	The AP Statistics Exam: An Insider's Guide to Its Distinctive Features
Chance and Peck (2015)*	From Curriculum Guidelines to Learning Outcomes: Assessment at the Program Level
Moore and Kaplan (2015)*	Program Assessment for an Undergraduate Statistics Major
Resampling	
Cobb (2007)	The Introductory Statistics Course: A Ptolemaic Curriculum?
Hesterberg (2015)*	What Teachers Should Know About the Bootstrap: Resampling in the Undergraduate Statistics Curriculum
Tintle et al. (2015)*	Combating Anti-Statistical Thinking Using Simulation-Based Methods Throughout the Undergraduate Curriculum
Wild et al. (2015)	Accessible Conceptions of Statistical Inference: Pulling Ourselves Up by The Bootstraps
Communication, capstones, and statistical practice	
Higgins (1999)	Nonmathematical Statistics: A New Direction for the Undergraduate Discipline
COPE (1999)	Ethical Guidelines for Statistical Practice
Lazar, Reeves, and Franklin (2011)	A Capstone Course for Undergraduate Statistics Majors
Fi and Degner (2012)	Teaching Through Problem Solving

(continued on the next page)

Çetinkaya Rundel and Stangl (2013)	A Celebration of Data
Cohen (2014)	Ethics for Undergraduates
Bryce (2005)	Developing Tomorrow's Statisticians
Stodden (2015)	Reproducing Statistical Results
Nolan and Temple Lang (2015a)*	Explorations in Statistics Research: An Approach to Expose Undergraduates to Authentic Data Analysis
Smucker and Bailer (2015)*	Beyond Normal: Preparing Undergraduates for The Work Force in a Statistical Consulting Capstone
Theoretical statistics	
Nolan and Speed (1999)	Teaching Statistics Theory Through Applications
Nolan and Speed (2000)	Stat Labs: Mathematical Statistics Through Applications
Reid, Efron, and Morris (2003)	Is The Math Stat Course Obsolete?
Horton, Brown, and Qian (2004)	Use of R as a Toolbox for Mathematical Statistics Exploration
Chihara and Hesterberg (2011)	Mathematical Statistics with Resampling and R
Horton (2013)	I Hear, I Forget. I Do, I Understand: A Modified Moore-Method Mathematical Statistics Course
Green and Blankenship (2015)*	Fostering Conceptual Understanding in Mathematical Statistics

> Statistical theory has most commonly been taught in the second semester of a year long sequence in probability and mathematical statistics. While that course is not unacceptable, the usual version is neither representative of modern statistical practice nor a good introduction to statistical thinking, and we encourage alternatives. For example, the applied regression and theory courses might be replaced by a two-semester sequence combining theory and applications (Tarpey et al. 2000).

Do our bachelor's graduates have the needed skills to compute with data in the manner described by Nolan and Temple Lang (2010, 2015b)? Knowledge of a variety of statistical methods along with the ability to assess their potential and limitations is useful, but if an analyst cannot wrangle data in a form to answer a statistical question, their utility may be limited. Our curricula need to prepare students engage in the entire data analysis process. The value that statistics brings to this enterprise needs to be highlighted and communicated, while other skills and capacities are added to our programs.

We note George Cobb's apt metaphor (Cobb 2015a) comparing changing curriculum to moving a graveyard: this squares with our experiences. We also agree that "Our territory—thinking with and about data—is too valuable to allow old curricular structures to continue to sit contentedly on their aging assets while more vigorous neighbors take advantage of the latest ideas" (Cobb 2015a). How do we ensure that students have flexible problem-solving skills to tackle future problems using data with techniques and technology that may not yet exist?

The work of the ASA undergraduate guidelines working group (and the team that drafted the original ASA guidelines in 2000) leveraged a number of articles and resources that have helped to define the undergraduate statistics curriculum. Table 2 includes a selected set of articles (many published in *The American Statistician*) that are particularly noteworthy or groundbreaking. Readers are encouraged to familiarize themselves with these articles as part of ongoing curricular review.

In this issue, we have assembled a set of articles that help describe a way forward. This includes a provocative article by George Cobb that is accompanied by an online supplement with 19 responses to the paper from an international group of statisticians (Albert and Glickman 2015; De Veaux and Velleman 2015; Fisher and Bailer 2015; Franklin 2015; Gelman and Loken 2015; Gould 2015; Holcomb, Quinn, and Short 2015; Kass 2015; King 2015; Lane-Getaz 2015; Notz 2015; Peck, Chance, and Rossman 2015; Ridgway 2015b; Temple Lang 2015; Utts 2015b; Ward 2015; Wickham 2015; Wild 2015b; Zieffler and Justice 2015; and a rejoinder, Cobb 2015b). These discussion responses and rejoinder plus other resources related to the undergraduate statistics curriculum can be found at *http://www.amstat.org/education/curriculumguidelines.cfm*.

We hope that this collection of articles as well as the online discussion provide useful fodder for further review, assessment, and continuous improvement of the undergraduate statistics curriculum that will allow the next generation to take a leadership role by making decisions using data in the increasingly complex world that they will inhabit.

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