Rejoinder to Discussion of "Mere Renovation is Too Little Too Late: We Need to Rethink Our Undergraduate Curriculum from the Ground Up"

George W. COBB

1. Introduction

What a failure! I worked so hard to be provocative only to have Gelman and Loken call me "typical," have DeVeaux and Velleman dismiss me as "beside the point," and have Notz fantasize that I might be only "a bad dream."[1] Wild, obliquely through his title, sneers at my challenges: not far enough, not fast enough, and not broad enough. Clearly my race is run. I was right to retire five years ago.

Of course my sample of characterizations is grossly biased, both by selection and by quotation out of context. In reality, I feel honored that so many colleagues whose work I have long admired have taken the time to read what I wrote, to think deeply in response, and to write such a variety of original comments. What a picnic! I won't go there, however; at least not in musteline clothing. But picnic, yes: I and all the respondents agree in wanting to make our blanket-buffet of statistics both more attractive and more substantive. In particular, we can agree with Fisher and Bailar that ours is a time of opportunity.

In what follows, rather than respond individually to the 19 sets of authors one at a time noting points of agreement and disagreement, I attempt to synthesize and respond by categories of topics. Accordingly, Section 2 summarizes and celebrates the variety of innovative courses and programs described in the responses. Then Sections 3 and 4 address two apparent misunderstandings and two major disappointments. Next, Section 5 offers a summary of the challenges and strategies for reform suggested by the respondents, and Section 6 follows with a call to redirect research in statistics education to help meet those challenges. Section 7 outlines a triangular tension: our subject, our university departments, and our U.S. liberal arts colleges. A valedictory Section 8 concludes on a note of constrained optimism.

2. Our Resplendent Picnic of New Programs

A disadvantage of the response/rejoinder format is that points of disagreement tend to get more space in the rejoinder than do points of agreement. There is far more to celebrate in the many innovations described in the responses than the length of this section might suggest. The academic levels of these innovations span the range from K–12 through graduate school (and beyond: Utts urges "continuing education" and Gould urges "K-retirement"). The institutions impacted include grade schools and high schools, all levels at four-year colleges, and graduate programs at universities. The scope ranges from single courses to entire programs, many of them interdisciplinary. The approaches are equally varied. Many could be seen as anticipations of the Horton report (ASA, 2015) in their emphasis on data science and/or their reliance on experience working with real data to address an applied challenge of genuine import.

To take space to summarize each of the innovations I applaud would duplicate what the respondents have already written, and so instead I urge any readers who have not read these responses to do so. Here, briefly, are summaries of five innovations, one that serves to illustrate the core recommendations of the Horton report, and four others that fall outside its convex hull. I list them from the one I consider most at the center to the one I consider extreme.

- *Chance/Peck/Rossman: A new kind of introductory course.* To paraphrase, California Polytechnic Institute at San Louis Obispo now offers a course for entering first quarter students that begins their majors' discussions of the historical roots of the discipline, of ethics, and of future directions, while introducing big data, computing in R, communication, and collaboration skills. Is it any wonder that for me the trio Chance/Peck/Rossman suggests "CPR" for our beginning course?

- *Gould: "bringing a 'data science' curriculum to high school."* Gould's project "Mobilize" is funded by the National Science Foundation. For me what stands out here is Gould's emphasis on teaching statistics within the context of the entire process of scientific investigation *at the high school level*. This goal resonates with the Horton report's attention to statistics as an integral part of the scientific enterprise, but also puts Gould's project in the vanguard of those who would challenge the entrenched Advanced Placement curriculum, its lingering obeisance to probability, and its tradition of mathematically oriented teachers.

- *King: A voice from industry*. The teaching of statistics has long been beneficiary of colleagues who work in business, industry and government, and who care also about education. I am happy to salute King for contributing to this important and valued tradition. I enthusiastically support what I see as her three main imperatives: (1) Recruit early, in high school, from students in Advanced Placement courses in calculus, statistics, and computer science; (2) encourage early, at the sophomore level in college, a

Online discussion of "Mere Renovation is Too Little Too Late: We Need to Rethink Our Undergraduate Curriculum From the Ground Up," by George Cobb, *The American Statistician*, 69. George Cobb is Senior Research Professor, Department of Mathematics and Statistics, Mount Holyoke College, South Hadley, MA 01075.

[1] Here and after, when I cite invited comments, I omit the redundant 2015.

commitment to an applied subject, and (3) expect and face the challenges of implementation.

- *Ward: Learning communities.* Alone among the responses, Ward's focus is on sociology more than cognition, and describes a program already in place at Purdue University, one that anticipates my thesis in Section 6 that we need a new direction in our research on statistics education. Ward's learning community at Purdue "could be implemented nationwide. The Purdue Statistics Living Learning Community blends the academic, research, residential, and professional development experiences of 20 sophomore students per year." Clearly, there are issues of staffing and scale, but the Ward model is an inspiring example.

- *Wickham: A grammar of statistics.*[2] Wickham argues that our goal should be to develop a "grammar of statistics" as a framework that will allow us to broaden the "safe" use of statistics to a vast population of statistical "amateurs."

Modern theory of finance identifies a curve—the "efficient frontier"—that defines the tradeoff between the maximum expected return for a given level of risk. As one might anticipate, the higher the acceptable risk, the greater the expected return. I regard the efficient frontier as a metaphor that applies broadly to all human investments in our future, and applies in particular to our efforts in education reform. Thus I see a tradeoff between trying for a small change with a large chance of enlisting a major following, and, at the other extreme, trying for a much larger change with a correspondingly smaller chance of broad-based impact short term. In brief, attempts at reform are constrained: the bigger the step forward, the smaller the audience that will choose to follow.[3] In this context I regard Wickham's proposal for a "grammar of statistics" as the most ambitious of all the proposed innovations. It has the potential to revolutionize the way we think about data analysis and about how we teach it. At the same time, because it promises to be such a major step in a new direction, it may prove to be too far ahead of its time to gain traction short term. (See footnote 3.)

In choosing these previous five innovations to single out, I do not mean to downplay my admiration for any of the others. They may be closer to the mainstream of reform as set out in the Horton report, but for that very reason they may be more likely to attract followers in the short term, and thus more likely to have broader impact short-term.

I now turn to a pair of points where I wasn't clear enough, and another pair where I was disappointed.

[2]When it comes to statistics education, Christopher Wild advocates "courtship" and Hadley Wickham urges "safe sex." Exploring such metaphors is beyond the scope of this rejoinder, and so is left as an optional exercise for the reader.

[3]As a salient example, consider Peter Nemenyi, a Hungarian born mathematician who fled the Nazis and became a U.S. civil rights activist. Few teachers of statistics know his name, but in the 1960s he created and taught a randomization-based introduction to inference at the historically black Hampton Institute in Virginia, now Hampton University. Decades after Nemenyi, Gottfried Noether at University of Connecticut and Frederick Mosteller at Harvard wrote textbooks for courses in the same spirit. Only in the past decade, 50 years after Nemenyi, decades after Noether and Mosteller, has the idea of such a course begun to gain traction.

3. Two Failures to Communicate: "I Thought I Was"

Several comments brought to mind an old story about the notoriously taciturn Thomas Dewey, meeting the press as part of his 1948 run for President. "Smile, Governor," a photographer pleaded, to which the dour Dewey, taken aback, replied, "I thought I *was*." In a similar spirit, I was somewhat taken aback by two sets of comments I thought I had anticipated and addressed in response to helpful comments by reviewers of my initial draft. In short, "I thought I *was*."

- *The tear-down.* It is not our *curriculum* that is the tear-down, but rather, less drastically short term, but more ambitiously long term, it is our *thinking* about curriculum that needs to start from the ground up. Unless I misread, not one of the respondents wants us to continue to debride the skins of our noses on the same old curricular grindstone. We all want change. All the same, our thinking about change is too somnolent.

The distinction between *how we think* and *what we do* needs to be recognized more explicitly. What we *do* is constrained by reality. How we *think* is not, and should not be. To borrow from Robert Browning (1855), our reach should exceed our grasp. None of the respondents struck me as clear enough about this difference. Some accuse me of wanting to tear down our existing curriculum. I don't. What I do want is for us to seek out and question some lurking assumptions that shape the way we teach. As I see it, one of the biggest general issues in statistics education, one that may prove pivotal for our future, is the tension between mathematics and data, between abstraction and context, between theory and story. We statisticians have come mainly from mathematics: Mathematics has been our computational engine, our source of underlying theory, and in the undergraduate curricula since the 1950s, our path to respectability. By tradition, our allegiance is to mathematics. But mathematics insists that we understand, learn, and teach top down: Theory dominates, data merely illustrates. This too-often-unconscious hierarchy of priorities in our thinking about curriculum is the tear-down.

To recycle a simile, the tear-down is our mathematically driven tendency to treat topics and courses as structured like a pyramid: Knowledge comes in hard rectilinear blocks. You have to complete the first layer of blocks before you start the second one; you can't talk about *xyz* until you've talked about *rst* and *uvw*, all the way back to *abc*. Transferring this logic from the mathematics curriculum to, for example, how we learn to read exposes its flaws for teaching how we learn from data. We don't learn to read three letters at a time; rather, we learn the way De Veaux and Velleman want us to teach, holistically. In learning to read, once we get past the stage of what for my generation was "See Spot run. Oh, oh, look," we come to experience learning as a kind of archeological dig in which we put the pieces together as we gain depth. Different students learn different things in each of their courses, depending on their backgrounds, but for each student, the threads of new information and new ways of thinking get woven into a pre-existing and ever-evolving tapestry of understanding.

I've responded here to those for whom I failed to make clear my sense of what it is that needs to be reimagined from the ground up. Other respondents put their focus on obstacles and challenges. Although I agree with their concerns, I would be sorry to have the genuine boulders in our uphill path distract us from trying to anticipate the thrill of the long view from above tree line.

• *Breiman's dichotomy.* Of course De Veaux and Velleman are right to say that we should teach "holistically," but their "beside the point" is beside the point. To recognize a neglected polarity as Breiman has done is not to argue for a forced choice. As I read Breiman, his main point was not that we must choose one or the other, not that we should abandon probability-based analysis, but rather, that our current synthesis fails to recognize the importance of the kind of thinking he (unfortunately) named "algorithmic." Breiman was not arguing for either/or, but for balance, integration, and attention to the relationship between the available data and the goal of the analysis. So was I. So are De Veaux and Velleman.

I continue, as urged by Chance, Peck, and Rossman, to explore the fruitful tensions between Breiman and B&K: In thinking about curriculum, how can we best understand the role of probability? The comments of Kass help push this exploration forward, and I agree with his censure of authors who "have done nothing to indicate that [their method] performs well." Are there alternatives to probability-based models for this purpose? In this connection I also find it helpful to keep in mind, as I tried to point out myself but Loken and Gelman state more clearly, that "algorithmic" is not the same as "anti-probability." Finally, I wonder whether and how we can justify a probability model for what Gould calls "algorithmic data."

4. Two Disappointments: A Pier Into the Future?

In James Joyce's *Ulysses* Stephen Dedalus defines a pier as a "disappointed bridge," leaving implicit its failure to reach the intended destination (Joyce, 1922). Sadly, two of my more heartfelt attempts at a bridge to the future remain largely disappointed, short of the shore I had hoped to reach. They are: flattening prerequisites and teaching Bayes early.

• *Flattening prerequisites.* Few of the respondents commented directly and in substance on my argument that we can teach many core concepts and methods of our subject—applied Bayes, design and ANOVA, regression, and what is traditionally mislabeled "mathematical" statistics—*without* most of the traditional prerequisites.

I salute Lane-Getaz for being an exception. In her response, she describes a second statistics course at St. Olaf that teaches students of the social sciences much of the content they might otherwise learn in a graduate-level course in quantitative methods.

Even more radically, Ridgway encourages us to recognize that computers and visualization can engage students early and directly with multidimensional and nonlinear relationships. We should not *assume* that students can *only* understand multivariate data if they climb our familiar step-ladder, one dimension at a time. Step one, histograms. Step two, scatterplots. Step three, two-way additive models. Step four, interaction. And on and up. Ridgway shows us a different path.

We should all embrace the concern of Holcomb and Moreno that for many students across the country, as at their two institutions, mathematical expectations can be a major obstacle. Unless we flatten prerequisites, we bar the way to such students. But: If we do flatten prerequisites, where and when will students who aim for graduate school learn the mathematics they will need for admission? Finding answers to this question is critical. Here are three possibilities: (1) Change some of the ways we teach mathematics to students of statistics. (2) Change some of the expectations of graduate programs. (3) Recognize that more and more careers with data don't require a traditional graduate program. In more detail: (1) For some students, and at some institutions, it may work to teach applications first, and use that background to support the teaching of mathematics. For example, many teachers of mathematical statistics urge students to take Stat 101 first. More radically, as described in my article, it is possible to teach the concepts of mathematical statistics with only a prerequisite of a single semester of calculus. Probability can come later. (2) Many traditional PhD programs want incoming students to have learned mathematics through the level of a rigorous course in real analysis. The need for these students continues undiminished, but the need for other data-oriented graduate students without that background continues to grow. (3) As Utts points out, "the reason for having an undergraduate degree in statistics is changing rapidly," with more opportunities for jobs right after graduation, without the need for graduate courses.

In the spirit of Holcomb and Moreno, although I applaud Albert and Glickman's urging us to teach a course based on generalized linear models, I was disappointed to read that "this would require students to have knowledge of a variety of probability models." Why not teach those models, as needed, in the context of analyzing real data?

I agree with Wild that our aim should not be just to offer a "smorgasbord" of courses each covering "a small number of 'advanced' topics at an intro level." That aim, however, was not the point of my examples. In no way did I mean to suggest that we should revise our curriculum just by offering more flavors of Stat 101. Quite the contrary. My point was and is that if only we choose to, we can for many strong students skip Stat 101 altogether and offer instead courses that allow good students to learn important areas and real applications at the level of a second course, teaching the necessary Stat 101 concepts along the way. In short, we can, with modest effort and thought, revise existing intermediate courses to teach the same content without a statistics prerequisite. If we statisticians don't do it ourselves, others will do it for us. (I may be guilty of a manufactured disagreement here, a la reality TV. Anyone who knows inZight (Wild, 2015) knows that Wild wants to flatten prerequisites as much as I do.)

• *Teaching Bayes early.* I was doubly disappointed here. First and foremost, I was disappointed that only 3 responses out of 19 highlighted the importance of teaching Bayesian thinking. Surely the fraction 3/19 far under-represents the role of applied Bayes in our current practice. I agree emphatically with Albert and Glickman that "the time is right for the development of an applied Bayesian course," but why not a Bayesian version of Stat 101? Thus I was also disappointed that the few responses that did mention Bayes were heavy in their emphasis on prerequisites. I disagree with Notz that "to introduce Bayesian thinking students need to know something about probability distributions, conditional probability, and Bayes theorem." As I see it, this untested assumption (a call for education research!) bears substantial responsibility for the failure of past attempts to teach a Bayesian elementary course. As I have suggested, we can get by with far less formal probability than is usually assumed, and what little is truly essential can be taught along the way as needed in a Stat 101 course with a Bayesian orientation.

Albert and Glickman cite the textbook by Link and Barker (1999) as the basis for a "nice applied Bayesian course" and so, full of hope, I ordered a copy. Sure enough, it is a lovely book with an impressive collection of deep and interesting applications, but it implicitly requires three semesters of calculus and a semester of probability.

Utts is right that new textbooks can lead the way. Our profession urgently needs a new textbook for teaching applied Bayes at the introductory level. I hope for a book along the lines I have suggested, one that relies on Laplace's version of the likelihood principle to avoid the need for any of the usual formal mathematics. No marginal probabilities, no Bayes Theorem, and no calculus. Laplace's eighteenth century genius together with our twenty-first century computer simulations reduce the basic idea to a simple fraction $P(\theta|y) = \frac{\#(\theta|y)}{\#y}$. Adjustments for continuous distributions and prior probabilities are straightforward. (More research, please.)

I regard both of my two disappointments as strong support for my assertion that our *thinking* about curriculum is indeed a tear-down. We have the content already, but our thinking about how to make that content accessible to talented and motivated undergraduates remains immobilized in a spider web of old assumptions. Tear down that web!

5. Implementation: Principles, Obstacles, Challenges, and Strategies

My goal in what I wrote originally was to float high and take a long view, as a counterpoint to the Horton reports appropriately more practical and tethered emphasis. Many of those who wrote in response to my article have chosen to drop lead in my basket and drag my balloon back to earth. They emphasize obstacles to change and challenges to making change happen. Lane-Getaz reports on her own very real experience with resistance to change. Gelman and Loken are right that "developing a forward-thinking approach is not so easy" and I share with Utts her "pessimism about implementing" calls for change. Here again, however, we need to render unto reality that which is real, but only that much and no more. We should not let shadows of the short-term darken our vision of what we might accomplish with time and effort. Thus I am cheered that Utts, our ASA President elect, is no pessimist: " …we have come a very long way in a very short time. And the pace is quickening." Franklin suggests, and I agree, that our "two biggest challenges" are "building a culture that advocates this" and "the teacher preparation needed."

Teacher preparation—this one of Franklin's (University of Georgia) two challenges is clearly a major issue, one that many other respondents echo. Fisher and Bailar (Miami University) raise the same concern in connection with issues of scale and teaching thousands of students at an institution that relies on adjunct faculty who are paid too little to learn to depart from their familiar traditional course. Although Fisher and Bailar focus their concern on the introductory course, I think their worry about implementing change in fact applies to faculty at all levels. For example, at the high school level, Gould (UCLA), in connection with his NSF-funded *Mobilize* project, which seeks to engage students with the role of statistics in the process of scientific investigation, cites the challenge of teacher preparation. At the graduate level, Kass (Carnegie Mellon University) notes that "we have not penetrated into schools of education." Notz (Ohio State) also identifies teacher preparation as a major issue. Although other respondents chose to focus on other issues, it is hard to imagine that any of them would disagree.

Changing the culture is closely tied to teacher preparation, in that teachers help shape the culture, and culture helps shape teacher preparation. Along with Franklin, several others champion the need to reshape the culture of statistics education. Fisher and Bailar point out the need to enlist client departments. Holcomb and Moreno urge us to publicize employment opportunities. Temple-Lang has found that "data analysis competitions" are effective in getting students actively engaged.

More broadly, Kass writes that "the biggest challenge in statistics education arises from the difficulty humans have in accepting ambiguity and acting reasonably in the presence of uncertainty." I agree wholeheartedly. At the same time, I can't resist a chance to re-engage: I find it useful to make a sharp distinction between uncertainty, which can be described using a probability model, and ambiguity, which cannot. Random samples and randomized experiments lead *without ambiguity to models for uncertainty*. For data from other sources, *the connection to any possible model for uncertainty is ambiguous*. Gould articulates the challenge to our profession: How can we "find meaning in data that do not belong to the probability culture"?

Also on a general level, Zieffler and Justice ask: "how to get stakeholders to buy into the immense amount of work involved in curricular revision." At the risk of appropriating their ideas for my own purposes, I suggest that they offer an answer to their own question: by "using the tools of our profession—data and analysis."

6. Research in Statistics Education: Time for a New Direction?

To start with my punch line, I suggest here that based on the available evidence, our profession would benefit from a shift in the direction of research in statistics education, away from the cognitive psychology of understanding probability and its discontents, toward the social psychology of institutional change and its resistances. Gelman and Loken note (using Zieffler and

Justice's "tools of our profession") that my article "has more than 100 references, only one of which addresses empirical research in educational effectiveness." As a matter of principle I try not to argue with data, and so I plead guilty as charged. This observation and its implications resonate with a question posed more explicitly by Chance, Peck, and Rossman, who ask, "Do we test and evaluate before we tear down and build, or do we just tear down, build, and hope for the best?" I regard the question as deliberately crafty in its phrasing, and my short answer is "Neither one," but I take the question seriously, and so I devote the rest of this section and much of the next one to a longer response.

In my experience research in educational effectiveness is useful in helping us to understand which of our existing practices are more effective, which ones are less effective, and why. But in my experience, also, such research, though important for evaluating what already exists, tends not to be a source of new courses. As an example, I borrow from Utts: "What changed the landscape for Bayesian methods" was "a few innovative leaders who made it easy for others" to implement and teach these methods "by writing textbooks and computer programs." As I recall, a certain Gelman was one of those innovative leaders and authors who helped ease the way to Bayes for the rest of us.

To pursue the point, I think the history of our subject supports Utts's thesis that innovative textbooks are our engines of change. Here, with apologies for many omissions, is a severely pruned list, offered more as a provocation than as data. For more detail, I refer readers to my original article. In this list, I choose one major innovation for each of the last several decades, and one influential textbook author for each.

- *1950s: Making the teaching of statistics legitimate at the elementary level.* Frederick Mosteller (1961).
- *1960s: Teaching us to teach with real data, before computers.* John Tukey (1977).
- *1970s: Interactive computing and data analysis.* Francis Anscombe (1981).
- *1980s: Real data in the first inference course.* Freedman, Pisani, and Purves (1978); Moore and McCabe (1984).
- *1990s: Activity-based statistics.* Richard Scheaffer, et al. (1996).
- *2000s: Randomization-based inference.* Peter Nemenyi and others. (Note here that Nemenyi developed and taught his randomization-based course in the 1960s. It has taken us 50 years to catch up. For more, see footnote 3.)

What stands out for me is that *none of these pivotal innovations originated from research in statistics education.* Such research does not ordinarily lead to directly to innovations; rather, it documents whether and in what ways existing approaches do or do not help students learn. At the same time, it is important to be clear. I do not mean to disparage the importance of this research, only to sharpen our sense of its role. Such research has been instrumental in advancing our profession. Although I assert that it has not been a direct source of innovative textbooks, I do credit that research as a source of new thinking that can lead to innovative textbooks. (A prime example is Chance and Rossman 2015.)

To conclude this section, I offer a four-point summary.

- *Salute: The importance (past and continuing) of research in statistics education.* This research has played an essential role both in supporting and in shaping our teaching. It has helped all of us who teach to choose approaches that help students understand, and to avoid approaches that reinforce misunderstanding. It has helped us to understand which approaches enlist student interest and enthusiasm. It has, I am convinced, pushed us in those directions that have powered our extraordinary growth in student enrollments. In addition, this research has been essential to the success of proposals to granting agencies for funding in statistics education, and helpful to those agencies in their decisions about which projects to fund. Looking to the future, it seems clear that our need for research continues.
- *Premise:* As fellow statisticians, our colleagues who specialize in research on the teaching and learning of statistics should, following Zieffler and Justice, rely on data to direct their talents and efforts. What are the important open questions?
- *Open questions: What do we need to know at this point in our development?* I think the responses to my original provocation offer a clear consensus. According to the two dozen statisticians in our admittedly biased sample, the main challenges to statistics education at this point are not matters of cognition, but matters of implementation, as set out in Section 5. This matches the concern of funding agencies with "dissemination."
- *A new direction?* Based on the available data, I suggest that where we most need research is in the area of implementation rather than cognition. I make this suggestion with diffidence, knowing that so many colleagues who do this research have come mainly from a background in cognitive psychology, in the tradition of Kahneman and Tversky. For many of them, the attraction of research is the challenge of trying to understand the way students learn the probability-based aspects of statistical thinking. Nevertheless, I think this vein of research offers a dwindling source of new nuggets, and that evidence supports my argument for change. Sadly, perhaps, a background in cognitive psychology is no longer the best preparation for research that will help shape the future of statistics education.

As I see it, the argument for change is even more compelling when it comes to university graduate programs in statistics.

7. A Triangular Tension: Our Subject, Our Graduate Departments, and Our U.S. Liberal Arts Colleges

Gelman and Loken observe that I seem "to be concerned with the future of traditional statistics departments. . . " and they are right: I failed to be clear about the difference between our subject and our graduate departments. Their comment is especially clarifying in the context of observations from Wild. Together, Gelman, Loken, and Wild suggest a tension involving our subject, our university departments, and our U.S. liberal arts colleges. In this section (1) I argue, with Gelman and Loken, that the future of our subject is assured, (2) I agree with Wild that many university departments are bastions of conservatism, under siege and at risk, and (3) I expand on Wild's hope that liberal arts colleges can help lead our way into the future.

Our subject. The success of our subject—learning from data—is no more in jeopardy than is the role of money in politics. *Data, like money, will always be in demand. You can't have too much of it unless you don't know what to do with it.*

University departments. As recently as two decades ago, our subject and our university departments were aliased. No longer. Our subject threatens to outgrow many of its graduate departments. Wild quotes from Peter Diggle's (2015) address as President of the Royal Statistical Society: "I would like to see less statistics in undergraduate mathematics degrees." In effect, our subject may be important, but graduate schools don't want you to study it. Diggle's declaration calls to mind the Shakers, a now-extinct New England sect that expected to advance its agenda despite a ban on sexual reproduction. Can university departments survive if they rely exclusively on students who major in mathematics, study little or no statistics, but nevertheless choose to pursue a PhD in a subject they barely know? If you apply to graduate school in molecular genetics, you are expected to know something about molecules and genes. If you apply in astrophysics, the more you know about galaxies and quantum theory the better. No so for statistics. Only in our subject, alone among the sciences, do we hear, "Please learn as little as possible." The future of our subject may be assured, but the future of university departments in our subject is a different matter. We can all take a lesson from mules, who are both stubborn and unable to propagate.

Liberal arts colleges. As Wild points out, these "elite" four-year colleges are unique to the U.S. They stand out in many ways:

- *Faculty tend to come from PhD programs at top research universities.*
- *Teaching load is comparatively light*, four to six courses per year, as opposed to as many as ten per year at U.S. two-year colleges.
- *Greater emphasis on teaching excellence*, in comparison with universities and two-year colleges.
- *Curricular development is recognized as a form of scholarship.*
- *Comparatively small programs offer flexibility and opportunities for change.* Our subject is changing rapidly. Large programs, like ocean liners, can respond only slowly. Liberal arts college programs, like kayaks, can turn quickly to take advantage of the currents.
- *Curricular emphasis remains tied to the ancient trivium and quadrivium, with an enduring commitment to process over content.*

As my former dean, now president of New College (Florida) used to say, US liberal arts colleges are the places where cutting edge research from universities is brought into the undergraduate curriculum. (O'Shea, 2005) Faculty at these colleges have the connections to colleagues at research universities, the time, and the institutional support to create new courses and programs.

But wait: There's more! The commitment of liberal arts colleges to putting critical thinking first—putting process ahead of content, skeptical reflection ahead of vocational training—creates a particular resonance with statistical thinking. Statistics is about how we learn from what we can observe, and how we communicate what we have learned, the two fundamental goals of the ancient liberal arts. This value of the liberal arts was recognized decades back when the school of business at the University of Chicago established a fellowship program based on a study that found that a disproportionate number of CEOs of the Fortune 500 companies came from liberal arts colleges. The fellowship program, which offered a summer internship and guaranteed admission, was open only to students at a select 50 liberal arts colleges, and only to students whose major was *not* in economics or business.

8. Conclusion

I look forward, with constrained optimism, based on the following four-point summary:

- Although the future of our university *departments* and their entrenched graduate programs may be uncertain, the future of our *subject* is assured.
- Education research can best serve our subject and its teaching by a shift in emphasis away from the old *cognitive* psychology of probability and its discontents toward the *social* psychology of institutional change and its resistances.
- Undergraduate programs at liberal arts colleges will likely be nimble enough to respond to trends in statistical practice and to relevant contributions from education research, regardless of what happens in university departments.
- Best of all, across the board and at all levels, our profession's shared commitment to reliance on data will keep us working together.

Finally, I am grateful to the cited authors whose thinking prompted me to write, especially to my fellow statisticians who devoted their time to help create the Horton report (ASA 2015); to the editor and associate editors who helped with my thinking and writing, and who arranged for the online discussion; to the many reviewers whose comments advanced my thinking

and clarified my understanding; and to the discussants who have joined with me and with those I have relied on in contributing to what I am sure will continue to be an ongoing discussion. I am confident that readers will agree: our profession can count on thoughtful efforts such as theirs. In the spirit of Fisher and Bailar, although our time may be one of turmoil, in good hands turmoil creates opportunity.

Additional References

References listed in the original article are not repeated here.

Anscombe, F. J. (1981), *Computing in Statistical Science Through APL*, New York: Springer.

Browning, R. (1855), "Andrea del Sarto," in *Men and Women*.

Chance, B.L. and Rossman, A. J. (2015), *Investigating Statistical Concepts, Applications, and Methods* (3rd ed.).

Joyce, J. (1922), *Ulysses*, The Egoist Press.

Kahneman, D. and Tversky, A. (1974), "Judgment Under Uncertainty: Heuristics and Biases," *Science*, vol. 185, no. 4157, pp. 1124–1131.

Wild, C. (2015), InZight software, available online at *https://www.stat.auckland.ac.nz/~wild/iNZight/getinzight.php*.