# INCORPORATING A RESEARCH EXPERIENCE INTO AN EARLY UNDERGRADUATE STATISTICS COURSE

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*This paper describes guided interdisciplinary projects for early undergraduate courses that encourage students to experience the role of a research scientist and to understand how statistics is used in advancing scientific knowledge. An inquiry-based introductory lab activity walks students through a relatively advanced statistical topic. After the introductory lab, students conduct a research project that involves reading primary journal articles, developing their own research hypothesis, conducting a study, and presenting their results. The global warming hockey stick controversy described in this paper is one example of several intriguing real-world projects that can demonstrate the intellectual content and broad applicability of statistics as a discipline.*

## INTRODUCTION

In recent years, many successful reforms have been made to the traditional algebra-based, introductory statistics course. New emphasis on the incorporation of collaborative projects, conceptual understanding, genuine data sets, use of technology, and activity-based learning has tremendously enhanced students' understanding of the practice and application of statistics in a variety of disciplines. These changes have been found to be effective (Garfield, Hogg, Schau, and Whittinghill, 2002) and are endorsed by the American Statistical Association (ASA) and the Mathematical Association of America (MAA) (see, for example, Cobb, 1992; Cobb & Parker, 1998; Rossman & Chance, 2002). Richard Schaeffer (Moore, 1997) states that "with regard to the content of an introductory statistics course, statisticians are in closer agreement today than at any previous time in my career."

While great exemplars exist at the algebra-based introductory level, this paper addresses the need for more advanced statistics projects that also serve a general audience. Stat2Labs are interdisciplinary statistics projects for science, technology, and mathematics students that will provide a solid introduction to the intellectual content and broad applicability of statistics as a discipline while respecting the strong quantitative backgrounds of the students who take these courses. While these materials do introduce a variety of statistical techniques, the emphasis is on providing a structured approach to statistical thinking. Following the description of Wild and Pfannkuch (1999), these materials attempt to integrate statistical elements into the thinking patterns and strategies involved in problem solving within the context of a real-world problem.

These labs were originally designed as final projects in a first statistics course where students have strong quantitative backgrounds. Students were introduced to several homework and lab activities throughout the semester, and during the final weeks they were expected to complete and present a final project. In these types of final projects, students had a great deal of difficulty adjusting from traditional homework, or even daily lab activities, to a true research project. For example, students had trouble conducting literature searches, preparing proposals for analysis, properly collecting data, making the transition from a research question to a statistical model, as well as communicating their results.

At the same time, many of our client disciplines were encouraging their majors to conduct advanced research projects that often required more complex nonparametric or multivariate statistical techniques, which are not typically taught in an introductory statistics course. Most institutions require several mathematics and statistics courses before a student would be able to take applied classes discussing these topics. In order to address these issues, we collaborated with other disciplines to develop instructional materials with the following goals:

1) Broaden student understanding of the intellectual content and applicability of statistics as a discipline
2) Provide opportunities for math and statistics majors to interact with other scientific disciplines through interdisciplinary projects developed with faculty from several departments

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3) Strengthen student-faculty research by encouraging students to:
    - Read and evaluate primary literature
    - Emphasize the process of science and data analysis
    - Present oral and written reports with peer review
4) Incorporate the Guidelines in Assessment and Instruction in Statistics Education (GAISE, 2005):
    - Emphasize statistical literacy and develop statistical thinking
    - Use real data
    - Stress conceptual understanding rather than mere knowledge of procedures
    - Foster active learning in the classroom
    - Use technology to develop conceptual understanding and analyze data
    - Use assessments to improve and evaluate student learning.

Stat2Labs consist of projects that were created to emphasize the process of scientific study and data analysis from a statistician's perspective. These materials emphasize conceptual understanding, genuine data sets, use of technology and activity-based learning. Instead of simply assigning a final research project, these labs gradually create a methodology for students to follow when conducting research. While the statistical topics vary for each lab, each project encourages students to experience the role of a research scientist in 1) searching the literature, 2) preparing a proposal for analysis, 3) planning and carrying out experiments, 4) collecting data, 5) determining appropriate techniques for analysis, 6) integrating technology, 7) performing an analysis, 8) making inferences, 9) interpreting the results, and 10) presenting the results.

## THE PROJECT STRUCTURE

*Introduction to the Statistical Topic:*

Each project in Stat2Labs starts with a step-by-step workshop style introduction to a relatively advanced statistical technique. The labs emphasize statistical thinking and conceptual understanding where students consider a research question, develop a hypothesis, develop a statistical model, check assumptions, analyze real data and then interpret the results. While students do much of the work outside of class, the labs typically require about three 50-minute class sessions in a computer lab so students, in groups of 2 or 3, can work through the lab and ask questions. These labs were intentionally designed with step-by-step procedures, including software instructions in Minitab and R. We have found in our introductory statistics classes that students are fairly comfortable working through a step-by-step lab activity, even though the topics are beyond what are typically seen in an introductory class.

*Advanced Lab (Research Project):*

The advanced lab encourages students to incorporate the statistical concept taught by the introductory lab into another context. The advanced lab, which offers guided steps to strengthen the quality of student research, can be completed in 1-3 weeks. Though the statistical topics vary, each lab encourages students to experience the role of a research scientist: they read and evaluate primary literature in a discipline outside of statistics; they plan and carry out studies that emphasize the process of science and data analysis; they transition from research questions to a statistical model; they collect their own data or develop a simulation study; and they give oral or written reports with peer review.

After the introductory lab, each project includes a journal article or reading assignment that incorporates a statistical concept into another discipline. Reading primary literature is a new experience for many of these students. Guided questions are given to the students for peer review and evaluation of primary literature. This encourages the student to properly interpret the statistical terms used in the paper and broadens student understanding of the intellectual content and applicability of statistics.

Each lab encourages students to design their own unique research question. While students may not feel qualified to design a study, they often can suggest appropriate modifications to a study they have just reviewed, building upon previous work already conducted and published.

Students then conduct an experiment and analyze the results. Many steps are provided to ensure that students appropriately design studies and properly collect data.

Instructions on how to write a scientific paper or poster are also included for these projects. These include a detailed discussion on what should be in a title and author panel, abstract, introduction, materials and methods, results, discussion, conclusions, references and acknowledgements. Tips for presenting a poster as well as criteria for evaluating papers and posters are also given.

## EXAMPLE PROJECT: GLOBAL WARMING AND THE HOCKEY STICK GRAPH

*Introduction to the Statistical Topic:*

This lab discusses using principal component analysis to model an overall 2006 stock market value from indices such as the Dow (Dow Jones Industrial Average), the S&P (Standard and Poor's 500), and the NASDAQ (National Association of Securities Dealers Automated Quotations). The lab provides an introduction to principal component analysis in a simplified context with stock market values. These concepts are then extended to an advanced research project which discusses the process of reconstructing global surface temperatures. Both the stock market and climate change involve modeling changes over time and lend themselves to multiple indirect measurements.

*Advanced Research Project:*

This project is drawn from the 2006 congressional report authored by Edward J. Wegman which found that McIntyre and McKitrick (2003) were correct in claiming that Mann, Bradley, and Hughes (1998) used incorrect statistical techniques when creating their estimates of average global surface temperatures. The estimates by Mann et. al. (1998) have been widely used by the Intergovernmental Panel on Climate Change and other agencies as evidence that the 20th century was uniquely warm.

To reconstruct global surface temperatures, historical temperatures can be measured indirectly through proxies such as ice cores, tree rings, and coral growth patterns. After completing the introductory lab, students should feel comfortable using software to calculate the first principle component from proxy data.

Instead of using traditional techniques to calculate the first principal component, Mann, Bradley and Hughes (1998) state that they "…take a new statistical approach to reconstructing global patterns of annual temperature back to the beginning of the fifteenth century, based on the calibration of multi-proxy data networks by the dominant patterns of temperature variability in the instrumental record." This new technique essentially consists using a new type of standardization of each of the proxy variables. To account for the difference in scale, each series should be standardized to have a mean of zero and a standard deviation of one. Mann et. al. studied a time period from 1400-1980 (581 years of data for each of 70 proxy variables). Each of the 70 variables should have been standardized by subtracting the series mean (based on 581 entries in this example) and dividing by the series standard deviation (based on the 581 entries).

$$Z_{ij} = \frac{X_{ij} - \mu_i}{\sigma_i}$$

where i = 1,2,...,70 represents the 70 proxy variables and j = 1, 2,….,581 represents the 581 years of data points for each proxy.

However, Mann et. al. (1998) improperly standardized each variable. Instead of using the means based on the entire time period (all 581 entries), They used "truncated means", the mean from just the 1902-1980 time period (just the last 79 entries). Mann et. al. considered the use of truncating the means as a "new statistical approach". [Note: After the data were standardized with a truncated mean and standard deviation, Mann et. al. then divided the improperly standardized variables by their entire standard deviation (581 entries). However, this additional calculation has no impact on the analysis.]

Using truncated means increases the variance of any proxy variables showing temperature change in the last several years. When the covariance matrix is used on improperly standardized data instead of a correlation matrix, principle component analysis (PCA) will systematically select series with the largest variance into the first few principal components. Therefore, when truncated means are used, PCA is biased to select series (proxy variables) that show the hockey stick shape since these series have falsely inflated variances.

If just one of the 70 proxy variables has a higher mean in the last 79 years, the corresponding "standardized" variable using a truncated mean is likely to have a larger standard deviation than other variables, and thus is likely be weighed very heavily in the first principal component.

Students conducting this lab have been interested to know that Mann et. al. (1998) have denied errors in their reconstruction techniques and have continued with similar methodologies in later papers to create similar graphs that display a hockey stick shape. Instead of providing a mathematical proof as shown in Wegman's report (2006), McIntyre and McKitrick (2003) conducted a simulation study to show that Mann et. al.'s technique is invalid. In the simulation study, McIntyre and McKitrick repeated the following steps 10,000 times:

- Instead of using the 70 series of actual proxy data, McIntyre & McKitrick generated 70 series of random red noise data. Red noise is data with no systematic pattern, but has some correlation between adjacent observations (years) in the series. Each of the 70 series had 581 simulated random red noise "observations" representing the years 1400-1980.
- Mann et. al.'s truncated standardization was applied to each of the 70 random series. The 1902-1980 mean (instead of the overall mean) was subtracted and then the series was divided by the 1902-1980 standard deviation (instead of the overall standard deviation).
- McIntyre & McKitrick conducted PCA on the 70 series to find the first principal component.

Wegman's (2006) report found very similar results to McIntyre and McKitrick, however many people continue to defend the original "hockey stick graph" showing increasing earth surface temperatures. Wegman (2006) states "In general, we find the criticisms by McIntyre and McKitrick to be valid and their arguments to be compelling. We were able to reproduce their results and offer both theoretical explanations and simulations to verify that their observations were correct. We comment that they were attempting to draw attention to the deficiencies of the [Mann et. al.] type methodologies and were not trying to do paleoclimatic temperature reconstructions.... Generally speaking, the paleoclimatology community has not recognized the validity of the [McIntyre and McKitrick] papers and has tended to dismiss their results as being developed by biased amateurs. The paleoclimatology community seems to be tightly coupled as indicated by our social network analysis, has rallied around the [Mann et. al.] position, and has issued an extensive series of alternative assessments most of which appear to support the conclusions of [Mann et. al.]."

After discussing these articles, students have been eager to conduct their own study to determine if Mann et. al.'s (1998) techniques are correct. While the actual data is publicly available, I have found it easier to give students step-by-step instructions to reconstruct McIntyre and McKitrick's simulation. Then students are asked to design their own study, using different means, variances, correlations in the red noise random data, and criteria for identifying a "hockey stick" shape. Students are then asked to present the results of their own study, often in the form of a poster presentation, and discuss the implications of using improper statistical techniques in scientific research.

More information, including instructor resources, data sets, and student handouts including R-code for this project and other projects are available at:
http://web.grinnell.edu/individuals/kuipers/stat2labs/.

## CONCLUSIONS

Recent advancements in technology have made data collection and computationally intensive statistical techniques much more feasible. Thus researchers from many disciplines are now routinely using statistical methods developed in just the last few years. Huge data sets and automated calculations have made techniques such as traditional hypothesis testing much less essential, while areas such as pattern searching, simulation-based inference and nonparametric methods are becoming more important. This integration with multiple disciplines has stretched and grown the field of statistics into arenas never before explored.

These changes in statistics as a discipline have influenced successful reforms to the traditional introductory statistics course. These reforms emphasize understanding of concepts, interpretation, and data analysis instead of emphasizing formulas, computation, and theory. Curricula based on these reforms move away from teaching statistics as a collection of facts and toward teaching the scientific process of interdisciplinary data analysis as statistics are actually practiced. These reforms in the introductory statistics course have greatly enhanced students' understanding of the practice and application of statistics in a variety of disciplines. Unfortunately, much of the reform in undergraduate statistics education has been restricted to the introductory course (Moore & Legler, 2005) and there is a great need to extend these reforms to other courses (Brown & Kass, 2009).

Stat2Labs was created to provide expanded offerings in statistics at the undergraduate level that follow the principles of modern statistics education reform towards courses that are data-driven, technology-driven, and based upon active learning and authentic assessment. Guided research projects such as those presented in this paper encourage students to think like a statistician when working with advanced data analysis techniques. This helps students and future researchers in many fields understand the conditions under which studies should be conducted and gives them the knowledge to discern when appropriate techniques should be used. In addition, the variety of contexts encourage students to experience data analysis as it is actually practiced in multiple disciplines, by searching the literature, preparing a proposal for analysis, planning and carrying out experiments, and presenting the results.

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