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The Truth About Science: A middle school curriculum teaching the scientific method and data analysis in an ecology context

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The Truth About Science is a 40-lesson middle school curriculum module that teaches the process of scientific research, integrating mathematics and science concepts and skills. The goal of the curriculum is to teach students to think systematically and statistically about science inquiry. Students participate in each step of the scientific inquiry process, from asking testable research questions, designing unbiased experiments, and collecting their own data, to analyzing these data via graphical representations and statistical summaries, and communicating their research results as both poster and oral presentations. While the necessary statistical skills depend on difficult and abstract mathematical concepts, middle school students have been successful in applying them to their own research projects. The curriculum meets local and national standards in science and mathematics education and fills a gap in available educational materials. It has been piloted and revised through multiple iterations and published by the National Science Teachers Association Press. Feedback from teachers and students has been extremely positive.

Keywords: scientific method, K-12 mathematics, middle school science, statistics education

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1. Introduction

The early development of scientific and statistical thinking can increase student interest in, and recruitment to, scientific and statistical fields and raise the students' standards for evaluating and accepting information. However, currently available curriculum materials do not adequately address key scientific skills such as asking testable research questions or understanding the role of sample variability in data interpretation. To meet this need, a new curriculum was developed by scientists with experience in teaching students, in teaching teachers, in field ecology, and in quantitative analysis. *The Truth About Science* is a 40-

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lesson middle school science curriculum module that teaches the process of scientific research, integrating mathematics and science concepts and skills (Kelsey and Steel, 2001). The goal of the curriculum is to teach students to think systematically about the process of scientific inquiry. It begins with the formulation of testable research questions, and continues with the design of unbiased experiments, data collection, data analysis, drawing of conclusions, and presentation of research results.

Two features distinguish *The Truth About Science* curriculum from other currently available curricula. First, *The Truth About Science* teaches students to ask questions. Many recipe or lab curricula exist in which students answer a pre-formulated question by independently following prescribed methods. The novelty of these new materials is that they teach one of the most challenging parts of science—asking the question in such a way that it can be tested. Second, *The Truth About Science* fully integrates math and science by incorporating graphical and statistical analysis into middle school science materials. This curriculum was designed not only to meet science education standards, but also to meet or exceed national and local standards in mathematics.

Scientists and statisticians will appreciate this curriculum because the materials teach the foundations of scientific and statistical thinking to students at an early age. The experience and context of an independent research project provides a strong and concrete foundation from which to teach statistical lessons that may at first appear too abstract for middle school students. When middle school students have invested six weeks in designing their own research project and collecting the relevant data, they are highly motivated to understand those data and to examine them using the graphical and statistical techniques that scientists use.

2. Curriculum overview

Scientific investigation involves skills that must be learned and then practiced. To meet this need, *The Truth About Science* is composed of two kinds of lessons. Each new scientific skill, such as asking testable research questions, designing repeatable data collection methods, controlling for extraneous or confounding factors, or calculating t-statistics, is taught in a skill-building lesson. As students learn these new skills, they immediately exercise them in their long-term research project (LTRP). Through a series of integrated LTRP lessons students follow the steps of scientific research, applying the new skills they are learning. They formulate their own research question, design and conduct their data collection, analyze their data, and present their research results both orally and in poster format. To successfully complete the LTRP, students must apply all the scientific skills they have learned.

The LTRP is the centerpiece of the curriculum. Students conduct science research as practicing scientists do. The project provides a purpose, context and motivation for learning science and mathematical skills and concepts. To build and reinforce scientific thinking skills, the curriculum is organized into four sections: Research Questions and Hypotheses, Experimental Design, Analysis and Interpretation of Results, and Presentation of Research Results. Each section contains background information for the teacher and approximately 10 lessons.

The focus of the first section, Research Questions and Hypotheses, is asking testable research questions. Students also learn to differentiate quantitative versus qualitative

Table 1. Sample student questions for the long-term research project (LTRP).

Do more ferns grow on the ground or on logs?
Do more bugs live under conifer or deciduous trees?
Are mushrooms healthier in the shade or in the sun?
Are there more water insects upstream or downstream?
Is there a difference in the number of birds by the lake and by the buildings?
Is there more acid in the lake or the stream?
Are there more invertebrates found in pond scum or creek scum?
Does the water flow faster in the narrow or wide areas of a stream?
Are more pill bugs found in rotted wood or under rocks?
Is fast-moving water warmer than slow-moving water?
Is there a greater diversity of invertebrates in blackberry bushes or tall grass?
Are there more microscopic animals on the edge of a pond or in the center?

observations and become familiar with the four components of a scientific report: introduction, methods, results, and discussion. The curriculum provides a simple structure for generating testable research questions. Research questions identify (1) an explicit comparison to be made and (2) a quantitative measurement for making that comparison. This structure helps to ensure a common format for later statistical testing. Students conclude the section by working in groups to formulate their own research question and corresponding hypotheses for the group LTRP (Table 1).

Concepts of experimental design are presented in the second section of the curriculum. Students build an understanding of treatment types (treatment and control), replication, randomization, and controlling for factors that might influence results by conducting a series of experiments. Students use the skills learned during in-class experiments to design objective research protocols for their LTRP.

Data analysis and data interpretation are covered in the third section of the curriculum. The emphasis is on quantitative skills used to understand data sets. These lessons, which use hands-on pedagogy, are described in detail in the following section. Again, students apply each new quantitative skill to the analysis of their own LTRP data.

In the final section, Presentation of Research Results, students focus on putting together their posters (Table 2) and preparing oral presentations. Using the peer review process, students review and critique each other's work and make corresponding revisions. In a final celebration, students give oral presentations to an audience of parents, teachers, and classmates. The students reveal the truth about science as they have experienced it.

3. Development of quantitative skills in a science context

The in-depth data interpretation and analysis section in this curriculum is unique in middle school science materials. While standards have been developed for probability and statistics education in mathematics and for investigations and data interpretation in science, the two are rarely integrated. Seven core quantitative lessons guide students and teachers in data analysis and in summarizing their research results (Table 3).

The foundation for the quantitative sequence begins in the earliest lessons. In the first lesson of the curriculum, students are given an intriguing material (corn starch and water

Table 2. Sample student LTRP results and discussion paragraphs from a class of 4th and 5th graders. Original punctuation preserved. Spelling has been corrected where necessary.

Is the lake colder where the stream enters the lake or in other parts of the lake?

Results: The average temperature of the lake at the stream's entrance is 9.17 degrees celsius, and the average temperature farther out towards the middle of the lake is 10.69 degrees Celsius. The reason the average toward the middle of the lake is higher is because one replicate was taken farther out than the others by a kayaker and the rest were only as far as we could throw. That one replicate greatly influenced our average. Without this replicate the average of the lake is 10.36 celsius. The P-value is 0.01. We used the average of 10.69 in finding our P-value. That means the odds of getting this data if our null hypothesis is 1%. Our null hypothesis states that there is no difference in temperature between the lake at stream's entrance and farther out in the lake.

Discussion: We think our original hypothesis is correct because the odds of getting this data if the null hypothesis is true. Our research showed that there is a difference in temperature between the area of the lake at the stream's entrance and farther out in the lake. Our results support our original hypothesis. We think that the lake is colder closer to the stream's entrance because of the run off. Run off is a cold layer of rainwater from hills that runs into the edge of the lake. . . . It would be interesting to see if the lake temperature gets warmer the farther you go into the center of the lake.

Are there more stream insects under the top bridge or the bottom bridge?

Results: We found a range of insects from 0–25 in one netting. The averages of the number of bugs found under the top bridge and the bottom bridge are different by 0.4.

The top bridge has one high number that affects the data. The number is 24. Without it the average is 5.3 instead of 7.3. the bottom has two high numbers, 20 and 25. Without it the average is 4.3, and it was originally 6.9. Without the extreme numbers the averages are farther apart. 1.0 instead of 0.4, but the number of bugs found under the top bridge is still higher.

The odds of getting this data if the null hypothesis is true is 50%. That is our P-value.

Discussion: We think our null hypothesis is true and there is no difference between the number of bugs under the top and bottom bridge. We think this because our averages for the number of bugs found under the top bridge and the bottom bridge are around the same number, 7.3 and 6.9. Also, our p-value is 0.50 which means the odds of getting this data if the null hypothesis is true is 50%.

If we did this experiment again we would not let our friend or anyone swipe the stream bed. Right after he touched the bottom of the stream we got high numbers of bugs in our netting.

mixture) to observe and practice making qualitative versus quantitative observations. The lesson emphasizes the importance of collecting quantitative data in order to draw objective conclusions that are supported by evidence. Students continue to collect quantitative data in subsequent lessons. In repeated iterations of experiments, students experience first-hand experimental variability, learning that one does not observe the same results with each iteration. These experiences encourage students to ask questions such as ''What influences variability in data?'', ''How do researchers limit variability?'', and ''How does variability affect interpretation of research results?''

Once students have designed their long-term research projects and collected their data,

Table 3. Core lessons on analyzing and summarizing results. Sequence of lessons and associated concepts demonstrates the integration of skill-building lessons and LTRP lessons in which students apply those skills to their own data. The sequence also demonstrates the reinforcement of key concepts.

Day	*Lesson*	*Skills and Concepts*
Day 21	LTRP: Tables Tell the Tale	Creating a table from field data
Day 22	Aqueous Averages	Intuition about averages; the effects of zeros on averages; the effect of data variability on averages; the effect of extreme values on averages
Day 23 and 24	LTRP: Graphing Data	Creating and labeling a graph; interpreting a graph; the proper display of zeros on a graph; the display of data variability; the display of extreme values
Day 25	Faux Fish Figuring	The normal distribution; samples and populations; the Central Limit Theorem; an average as an estimate of the population mean; the effect of sample size on the accuracy of the average as an estimate of the population mean
Day 26	Statistical Savvy	The three pieces of information from sample data that determine the likelihood of that data under the null hypothesis; definition of a p-value; intuition about p-values; the effect of data variability on p-values; the effect of extreme values on p-values
Day 27	T-Test Practice	The three pieces of information from sample data that determine the likelihood of that data under the null hypothesis; definition of a p-value
Day 28	LTRP: T-Tests	Intuition about p-values

they begin the analysis of the data. First, they create a data table (Table 3—LTRP: Tables Tell the Tale). This step might seem obvious to a practicing scientist or statistician but it may be difficult for a 6th grader to organize research data for the first time. Learning to organize data in a meaningful way is critical to gleaning information from data.

Next, students encounter averages (Table 3—Aqueous Averages). They experience the concept of ''equal sharing'' or ''leveling out'' by redistributing colored water between clear cups. Several subtleties of averages are emphasized: summarizing data as an average does not capture variability, zeros are data points, and extremely large or small values can have a big influence on an average. Students then interpret example graphs, graph their own data, and apply their new interpretive skills to their own graphs (Table 3—LTRP: Graphing Data). The importance of describing variability, of including zero values, and of investigating outliers is re-emphasized in the graphing lessons.

Students explore the Central Limit Theorem and sample variability through simulations in Faux Fish Figuring (Table 3—Faux Fish Figuring). They gain understanding of the difference between populations and samples and are introduced to the normal distribution. Through actual experimentation, they discover that the sample average is a fairly good estimate of the population average. Students then observe the effect of sample size as they calculate and graph averages of three observations and averages of 10 observations from a known population. The lesson forces them to consider why the averages from two different samples of the same population often are different. The teacher asks, ''How would you know if the samples are just a little different but might have come from the same population or if the samples are so different that it is very unlikely that they came from the same population?''

In Statistical Savvy (Table 3—Statistical Savvy), students consider the information they would need to make a decision about the likelihood of getting these data under the null hypothesis (if the means of the two populations were the same). We encourage teachers to emphasize that students already have strong intuition on this topic. Students can usually identify the size of the difference between the sample averages and sample size (after the simulation experiment) as important information for making a decision about the likelihood of the data coming from populations with the same mean. Often, one or two students also remember the importance of the sample variance. The teacher demonstrates that a *t*-statistic is a mathematical process to summarize these three pieces of information into one number and a *p*-value is derived. Students are presented with two sample data sets and are asked to estimate a *p*-value. Surprisingly, the student estimates are usually close to the true *p*-value. Finally, students estimate a *p*-value for their LTRP data.

Teachers who are uncomfortable with the mathematics behind a *t*-test can choose to leave the data analysis and interpretation with the student estimate. However, many teachers choose to continue with the *t*-test lessons in which students calculate and interpret a *t*-statistic using calculators (Table 3—*T*-test Practice, LTRP: *T*-tests). The *t*-test ''recipe'' is easy to follow and students have a chance to perform it as a group with a designed, hypothetical data set before working on their own research project data. The lessons point out how each of the three important pieces of information (difference between the averages, sample size, sample variance) is incorporated into the recipe. A simplified *t*-table is included to obtain *p*-values.

While these are difficult and abstract concepts, it is possible for middle school students to learn and apply them to their research projects. Of course, one of the limitations in presenting this material is the expertise of the teachers. We have included extensive background information for teachers who have not had much experience with statistics or quantitative analysis of data sets. Some teachers have sent students to math class to do the data analysis lessons and analyze their data sets. Their students returned to science to interpret their results, write their reports, and design their oral presentations. Students have amazingly good intuition about probability and do not yet have the negative attitude toward statistics that many adults, and some teachers, have developed. Because students are analyzing their own data, they are extremely motivated to learn about these concepts.

4. Meeting national education standards

Training students to conduct scientific research as practicing scientists do is a logical way to meet many of the National Science Education Standards (National Research Council, 1996) and the mathematics standards set by the National Council of Teachers of Mathematics (2000).

Scientific standards describe fundamental abilities necessary for a student to do scientific inquiry:

ability to identify questions that can be answered through scientific investigations;
ability to design and conduct a scientific investigation;
ability to use appropriate tools and techniques to gather, analyze, and interpret data;
ability to develop descriptions, explanations, predictions and models using evidence;
ability to think critically and logically to make the relationships between evidence and explanations.

(National Research Council, 1996)

Mathematical curriculum standards require that the mathematics curriculum in grades 5–8 should include explorations of statistics in real-world situations so that students can manage the following tasks:

- systematically collect, organize, and describe data;
- construct, read, and interpret tables, charts, and graphs;
- make inferences and convincing arguments that are based on data analysis;
- evaluate arguments that are based on data analysis;
- develop an appreciation for statistical methods as powerful means for decision making.

(National Council of Teachers of Mathematics, 2000)

The data analysis and probability strand of the mathematics standards recommends that students formulate questions that can be answered using data and understand ''what is involved in gathering and using the data wisely. Students should learn how to collect data, organize their own or others' data, and display the data in graphs and charts that will be useful in answering their questions. This standard also includes learning some methods for analyzing data and some ways of making inferences and conclusions from data'' (National Council of Teachers of Mathematics, 2000). *The Truth About Science* clearly addresses both the current scientific and mathematical standards.

Since the national standards were released, many materials have been developed to help teachers convert their classrooms to standards-based classrooms. The first of the National Science Education Standards calls for inquiry-based science programs and almost all of the new materials claim to include inquiry activities. Inquiry in science has become the new buzzword, and, as such, conveys different meanings to different people. Using the national standards as a guide, inquiry-based materials can be defined as those materials that guide students to learn, understand, and perform the process of science research in a rigorous manner. *The Truth About Science* curriculum takes this process of science research and breaks it into conceptual pieces. At the conclusion of the program, students demonstrate their understanding and achievement in completing a true scientific inquiry research project.

5. Assessing teacher and student feedback

The Truth About Science was developed, piloted, and field-tested in middle school science classrooms in the Seattle Public Schools. Within this limited population, we have worked to find teachers who can apply the curriculum under a diverse range of conditions. The program has been used in self-contained 6th grade classrooms that follow an elementary model and in more traditional subject-based classrooms where the teacher sees close to 150 different students every day. The program has been used in schools where more than 50% of the students qualify for free and reduced price school lunches and it has been used in classrooms with a majority of students from middle class families. Many of the classrooms included special education students and some had English as a second language (ESL) students.

Professional development workshops for teachers have included multiple day workshops and co-teaching some of the more difficult lessons. Most teachers had limited, if any, experience conducting scientific research themselves. The teacher training workshops have required teachers to work in groups and conduct a mini long-term research project, as their students will do. Teachers state that this is a strong part of the workshop. The teachers learn to feel comfortable not knowing all the answers and guiding students to complete projects for which there is no single right answer.

After the first draft of the curriculum was produced, fifteen of the teachers who had been through the training were interviewed about difficulties they were having implementing the curriculum, modifications they had made, and suggestions for revisions to be included in the final product. Overall responses from the teachers were positive. Through the interview process, we found ways to revise individual lessons and we also found strategies for modifying the application of the curriculum.

We found that teachers who work with nearly 150 students each day have difficulty managing the ecology-based field projects. Their teaching schedules often don't allow them to spend 8–10 weeks helping students learn the scientific method. These teachers have used the skill-building lessons successfully in their classrooms and have skipped the long-term research project component. In the last quarter of the school year, many students prepare science fair projects for competition in the district science fair. Projects for this fair must demonstrate good science research practices. Teachers reported that the skill-building lessons helped their students feel more confident designing and completing science fair projects.

Many teachers have expressed their astonishment that middle school students are capable of completing a project of this magnitude and rigor. They praise the structure of the curriculum as it continues to build, reinforce, and apply concepts and they recognize the depth of learning experienced by the students. The following quote from one 6th grade teacher describes the astonishment very clearly:

> It is one thing to teach students how to write a scientific paper through library research alone, and a very different thing to have students implement important scientific processes in the field. . . . I can honestly say that students are engaged, they are learning, and they are excited to proceed with their own research projects.

Another teacher describes her experiences as follows:

> I was speechless the night of their (the students) presentation to their parents. I was so amazed to see the quality of their experiments and the enthusiasm from the children. Their presentations clearly spoke to the group of curious spectators. The students were able to deliver clear statistics and results of their efforts without missing a beat.

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References

Kelsey, K. and Steel, A. (2001) *The Truth About Science: A curriculum for developing young scientists*, National Science Teachers Association Press, Arlington, Virginia, USA.

National Research Council. (1996) *National Science Education Standards*, National Academy Press, Washington, D.C., USA.

National Council of Teachers of Mathematics. (2000) *Principles and Standards for School Mathematics*, Reston, Virginia.

Biographical sketches

Dr Ashley Steel is a quantitative ecologist with the Watershed Program at the NW Fisheries Science Center where she leads a series of landscape-scale projects for salmon recovery planning. She also conducts research on the effects of water quality on fish movements and survival. Her teaching experience includes six years at an academic summer program, pilot teaching *The Truth About Science*, and teaching as auxiliary faculty at the University of Washington. Dr Steel has a Ph.D. in Quantitative Ecology and Resource Management, an M.S. in Statistics, and an M.S. in River Ecology from the University of Washington.

Dr Kathryn Kelsey works for the Seattle Public Schools as a high school science teacher and a middle school science curriculum consultant. She also taught science at public schools in Benin, West Africa, and New York City. Dr Kelsey worked as a wildlife ecologist examining the effects of timber harvest practices within riparian corridors on stream-breeding amphibians and riparian wildlife species in western Washington. In her role as a teacher, she tries to guide students to work like scientists as they conduct their own science research projects. Dr Kelsey earned a Ph.D. in Wildlife Sciences from the University of Washington, an M.A. in Secondary Science Education from Columbia University Teachers College, and a B.A. in Human Biology from Stanford University.

Dr June Morita is acting associate Professor of Statistics at the University of Washington, and is a member of the National Research Center for Statistics and the Environment (NRCSE). Her Ph.D. in Statistics is from the University of California, Berkeley. Prof. Morita has received funding from the National Science Foundation, the Eisenhower Foundation, and the American Statistical Association to support her extensive work in professional development for K-12 teachers, particularly in statistics, data analysis, probability, and other areas of mathematics.