Data Collection and Organization (DC&O)

User's Manual

A BioQUEST Collection Module by
Frank Price Hamilton College

A BioQUEST Library VII Online module published by the BioQUEST Curriculum Consortium
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Acknowledgments

Thanks to Dr. Sue Ann Miller for the opportunity and help I needed to work through a specific example of how to computerize collection and organization of scientific data--and for the essential reality-checks.

Table of Contents

List of Figures

Introduction

By this time in your experience with BioQUEST, you should realize that learning science involves learning a variety of skills. You must learn to: absorb information; pose questions suggested by the information; design approaches to answering those questions; collect information (data) generated by those approaches; digest that information to come to some conclusion; and, finally, communicate your new understanding to others so as to persuade them of the value of your work.

Obviously, a crucial part of all of science (and BioQUEST) is the ability to manipulate a wide diversity of information. This is precisely where knowledge of computer software can be most helpful. Computers are not just word processors or mathematical engines, they are information manipulators -- of almost any information you can think of. And, of course, a knowledgeable computer operator can manipulate more information in more ways in less time than someone without a computer. Computers “empower” knowledgeable users.

The purpose of this module is to give you background and experience with some of the most useful general-purpose software tools available to you. Our aim is to discuss types of software that virtually every well-equipped scientist already needs, not programs used only by specific subdisciplines. While we are proud of our own simulations and other software, we can make a good case that all of BioQUEST’s goals could be accomplished using commercially available, generic tools. We will concentrate on what we call *generic* software and not burden you with the enormous variety of specialized tools such as those for scanning gels or controlling laboratory apparatus.

The generic software we will emphasize includes: *spreadsheets*, *data base programs*, *statistics packages*, *graphics*, and *word processors*. These are not programs that were developed by the BioQUEST team because there are many well-crafted examples already available from commercial sources for every brand of computer at reasonable prices. While we will use particular brands in our examples, we do not mean to imply that those are the best -- they are merely the ones available to the author.

The main messages we hope that you carry away include: an understanding of the types of information that you might want to put into a computer; what general-purpose tools are available and their strengths and weaknesses; how to choose the right tool for a particular job; how to take advantage of the power of the tools.

The Process of Science

To better understand the role of generic software in science, let’s look at one view of the process shown in Figure 1. We must caution you that the reality of science is a very dynamic, human activity and cannot be really captured in a static picture. Nevertheless, much of Figure 1 should be familiar and it will serve for the moment to focus our discussion.

Working from established information and paradigms (the heavy black box at the top), a scientist will formulate one or more questions and a research hypothesis to answer them. This is the first “P” of the BioQUEST 3P’s philosophy -- Problem posing. It is important to note that science is not an “objective” activity divorced from its cultural environment. A large number of preconceptions enter into the posing of scientific questions -- as with all other human activities -- and are reflected in the box in the upper left-hand corner of Figure 1.

Next comes the second of the 3P’s -- Problem solving. Traditionally, the scientist makes predictions about the results of experiments and then does the experiments. Many people don’t realize that experiments *per se* aren’t essential for doing science. If they were, evolutionary biologists and ecologists wouldn’t be able to do much science (not to mention astronomers and geologists!). So you should realize that predictions can also be about observations that have not yet been made. For example, an evolutionary biologist once hypothesized that dinosaurs were “warm-blooded.” Obviously, it is impossible to do an experiment to test this hypothesis. Nevertheless, several predictions could be derived from the hypothesis: that fossils will reveal anatomical structures and ecological characteristics of warm-blooded organisms. Scientists then reanalyzed previously found fossils to make new observations. These new data from old specimens supported the predictions: dinosaur bones often contain structures otherwise common only in warm-blooded mammals; the “predator:prey ratios” of dinosaurs are more like those of mammals than like those of cold-blooded lizards.

Some predictions cannot be tested with either experiments or observations. But all is not lost; many of these can be tested with computer simulations -- a strategy that we use quite a bit in BioQUEST. Not all simulations need to be done with computers; many can be done with what are sometimes called “thought” experiments -- a fancy way of saying that a researcher thinks through some question. Some of Einstein’s early work on relativity was of this sort -- he tried to visualize what it would be like to travel faster than light. Recently, computer scientists have been able to make Einstein’s vision available to the rest of us by programming computer simulations to produce “movies” of objects moving faster than light.

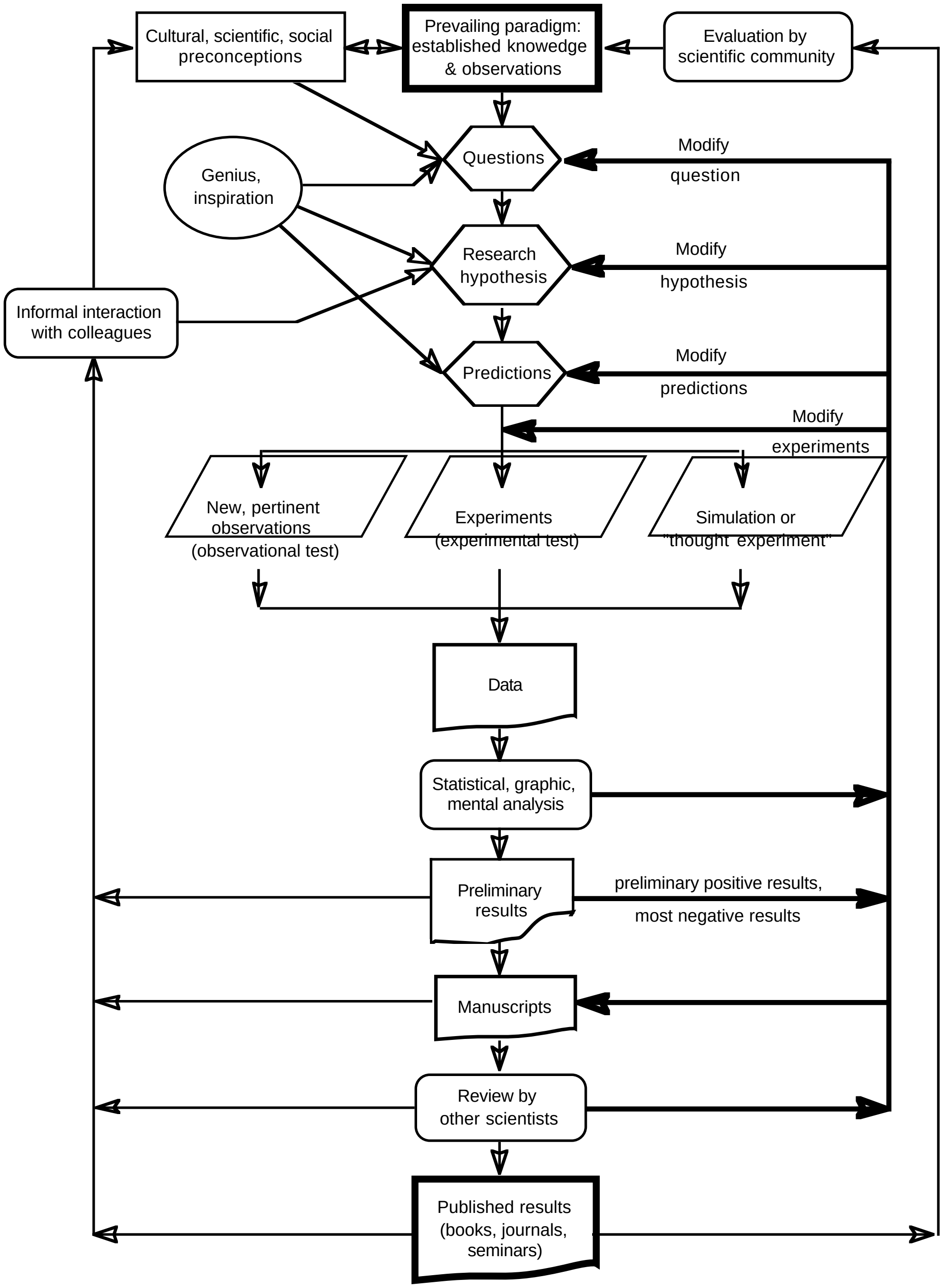


Figure 1. An outline of the scientific process. Existing, "public" knowledge is enclosed in a heavy, regular rectangle; hexagons enclose the preliminary stages of a scientific investigation; the three slanted rectangles enclose the "experiment" phase of a study; rounded rectangles denote processes of evaluation and analysis; rectangles with wavy bottoms show stages that traditionally are written on paper. The three hexagons constitute BioQUEST's Problem posing phase. The Problem solving phase extends from "Predictions" to "manuscripts." Persuasion is made up of the loops from "Manuscripts" through "Published results," "Informal interaction with colleagues," and "Evaluation by scientific community".

Whatever approach is taken, observations, experiments, or simulations generate results -- data -- information such as pictures, tables of numbers, patches of color on a gel or slide. The scientist then analyzes the data by a variety of methods to come to some conclusion. These preliminary results often suggest that the original questions, hypotheses, or predictions need to be revised, or may suggest changes in the design of the experiment, observations, or simulation. This “self-correcting” feedback (what computer types call debugging) is at the heart of the scientific process and is emphasized in Figure 1 by the heavy black arrows pointing up on the right side of the figure.

Once a researcher (or research group -- science is often done by teams) believes she has a good story to tell, she writes up her results as a manuscript and submits it to a publisher or journal. This is the last of the 3P’s -- Persuasion. The editor sends a copy of the manuscript out to others familiar with the research area for review. If the review is favorable (often accompanied by constructive suggestions), then the work is published as a book or journal article, or presented at a scientific meeting (heavy black box at bottom of Figure 1). Negative reviews also usually contain suggestions for improvement of the manuscript and research and are part of the heavy black feedback loop in the figure.

The black line on the far right side of the figure reflects the public part of science’s self-correcting feedback loops. Published data and hypotheses become part of the public body of science. The overall scientific community then has a chance to see how the new material fits in with established scientific knowledge and paradigms. A semipublic feedback loop also exists and is in reality part of the other loops, but is shown on the left for clarity and emphasis. Scientists are social creatures and are constantly talking among themselves. These informal interactions (and the friendships and antagonisms that go with them) play a major role in real science.

The Role of Generic Software

The roles that computers and software tools can play in science are as diverse as its disciplines and the researchers who practice it. Figure 2 illustrates some of those roles. The essential nature of computers is that they are information manipulators, so the answer to the question, “what can I do with a computer?” is, “what kind of information do you need to handle?” Figure 2 adds circles and arrows to Figure 1 to show types of computer applications that will concern us in this chapter.

One basic need is to collect and organize the data derived from experiments, observations, and simulations. Of course, computers may actually acquire the information in the first place. In many cases, the data are first captured in electronic form. Many modern instruments, from pressure and motion sensors to cell counters and satellite cameras, can output their results in computer-readable form. Many results that are not electronic, such as electrophoresis gels and electron micrographs, can be easily converted into electronic form, with a scanner, for example. Some data, such as DNA and protein sequences, are available from distant electronic data banks and can be “mailed” electronically to a researcher’s computer. When such easy input is not possible, many scientists type their data into a computer by hand.

But data acquisition does not concern us in this chapter (although you will use simulations extensively in BioQUEST to generate data). For this discussion we will take for granted that information has been accumulated in electronic form in the box marked Data.

First, consider the traditional approach to doing science: In Figures 1 and 2, the rectangles with the wavy bottom margins (Data, Manuscripts) represent stages which traditionally are written on paper with pen or pencil. In the rounded rectangle marked “Statistical, graphic, other analyses,” numeric data are sorted and counted by hand, written in columns subjected to statistical analysis, graphed, mapped, and written out. Results are written, then typed for submission to publications. It is at these stages that we wish to concentrate in this chapter, because there are a great many computer programs that can assist in all of these operations, and because in many ways these stages -- and the feedback loops to Questions, Research Hypothesis and Predictions -- are the heart of learning science.

Now, with computer technology, the traditional picture has changed. Almost everyone has some idea of how useful word processors can be. All too few have a good feel for the range of equally useful software tools that are available for collecting, tabulating, and organizing information. Depending on the type of information -- data -- you have and the analyses you wish to perform, you may find one or more of four types of software useful: statistical, data base, spreadsheet, and data graphics.

As Figure 2 suggests, data can be imported into any one of the four types of programs. (The programs have overlapping capabilities, and data can be moved easily from one type to another, a capability not shown on Figure 2 because it would have become too confusing.) The programs are then used to analyze the data to produce preliminary results -- hopefully answers to the questions that started the research. Typically, the results suggest modifications to the research program and the process loops around again. Which type of program to choose depends on the type of data, the type of analysis -- and often what the researcher has available and knows how to use. This chapter provides some guidance. The take-home message is that software can provide a rich toolbox for collecting and organizing data, especially if you have some experience with them.

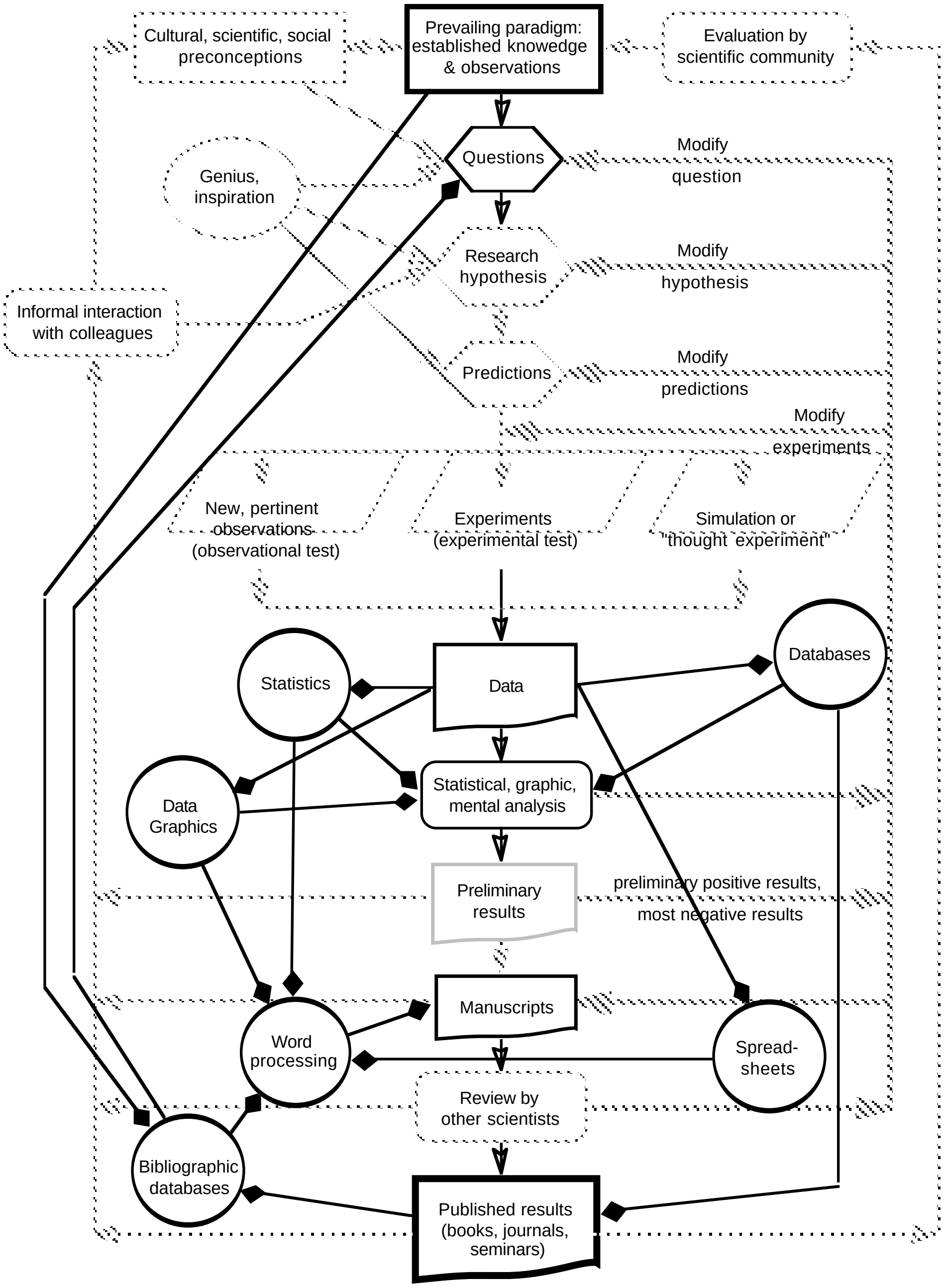


Figure 2. Where generic software fits into the scientific process. Figure 1 serves as a backdrop for the circles that show where various types of computer software interact with the scientific process. Note that these are just the most obvious, first-order interactions and much has been left out. The emphasis is on software used to analyze data (Problem Solving) and provide material for manuscripts (Persuasion). There are many less obvious software tools that could be included. For example, terminal-emulation or communication software is widely used to up- and down-load data to mainframe computers, and to send electronic messages (including data, preliminary results, manuscripts, and letters) to colleagues and publishers.

Types of Information and Tools

Before going into detailed examples, let's look briefly at the capabilities of the various program types. We will cover spreadsheets and data bases in detail, for they are most useful in collecting and organizing data. Other types of programs will be mentioned briefly to put them into perspective. Our purpose in this section is not to teach you any particular program, nor to catalogue all of the features of each type of program -- there are just too many and they vary considerably. Rather, we hope to give some feel for the variety of tools and their uses.

Spreadsheets

Spreadsheets are perhaps the most versatile of the generic tools for analyzing common types of data, especially numeric, so we will spend some time on them. If you have data that can be conveniently displayed as rows and columns, then you owe it to yourself to get one of these general-purpose, row-and-column manipulators. Not only can spreadsheets display and format numbers and text, they let you easily move rows and columns around (manually, or by automatic sorting), and can let you create new columns and rows (such as row and column totals and averages). This last feature means that many scientists who previously had to learn a programming language and write programs to do their analyses can far more easily do the same thing with a spreadsheet. Most spreadsheets will let you prepare simple graphs and charts of data, and can serve as simple data bases. Because of its versatility, spreadsheet software is probably the second program every scientist should buy. For many scientists, a spreadsheet can replace data base, graphics, and statistics packages.

Figure 3 shows a simple example of a spreadsheet that illustrates a common situation for faculty (and indirectly for students!). How long would it take you to calculate the 100 numbers and 40 grades in this example? Now, how frustrated would you be if you had to revise one of the exam scores and redo all of the calculations? After all of the calculating, how much time and interest would you have to think about the grades and their distribution?

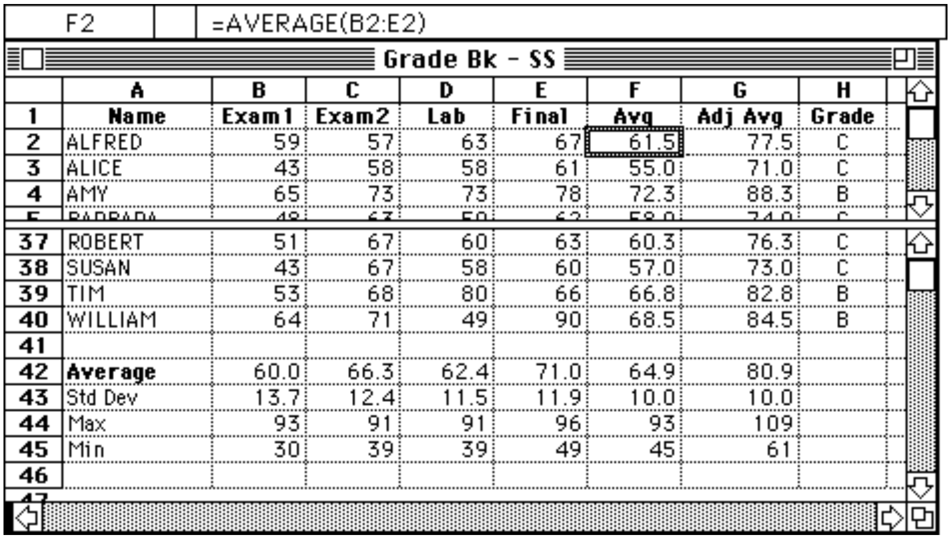
In Figure 3, the rows from 2 through 40 constitute the record for 38 students, columns B through E contain information on particular exercises, and columns F, G, and H summaries of students' performances. In the terminology of statistics, the student rows are "observations," "cases," or "records," the columns are "variables."

The cells of the spreadsheet are "alive": when one number is changed, all of the cells that depend on it change accordingly. For example, if Alfred's instructor discovered that the digits in his second exam had been transposed, and changed the 57 in cell C2 to

75, Alfred’s average, adjusted average, and grade, along with the average, standard deviation, and maximum of the second exam, average, and adjusted class average, would automatically be changed to reflect the new score.

Spreadsheets have many nice features to make working with rows and columns easy. For example, once the formulas in cells F2, G2, and H2 were entered, the instructor selected the rectangle of cells from F2 down to H40 by clicking on cell F2, holding the shift key down, clicking on cell H40, and then selecting a “Fill Down” menu command. In less time than it takes to read this, the formulas were copied down the three rows and automatically adjusted for row number, and the proper calculations performed. A similar, “Fill-Right” operation completed the summary table at the bottom. You can select and print a part of the sheet, and can divide the window into “panes” to show sections of the sheet that are not adjacent (as shown between rows 5 and 37 in Figure 3).

If the instructor wished, she could modify the spreadsheet to make it easier to assign letter grades and see their distribution (see Figure 4).

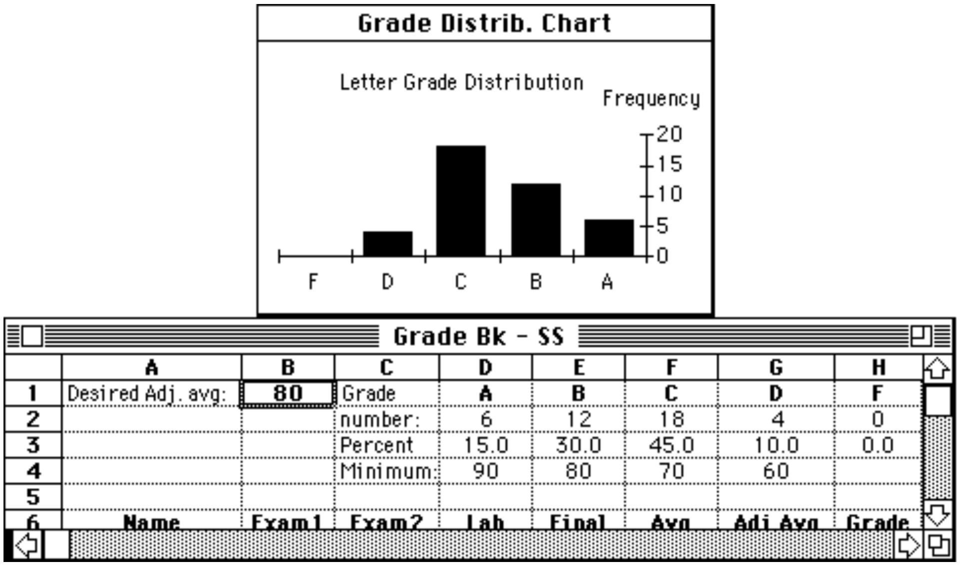


F2 =AVERAGE(B2:E2)

	A	B	C	D	E	F	G	H
1	**Name**	**Exam1**	**Exam2**	**Lab**	**Final**	**Avg**	**Adj Avg**	**Grade**
2	ALFRED	59	57	63	67	61.5	77.5	C
3	ALICE	43	58	58	61	55.0	71.0	C
4	AMY	65	73	73	78	72.3	88.3	B
37	ROBERT	51	67	60	63	60.3	76.3	C
38	SUSAN	43	67	58	60	57.0	73.0	C
39	TIM	53	68	80	66	66.8	82.8	B
40	WILLIAM	64	71	49	90	68.5	84.5	B
41								
42	**Average**	60.0	66.3	62.4	71.0	64.9	80.9	
43	Std Dev	13.7	12.4	11.5	11.9	10.0	10.0	
44	Max	93	91	91	96	93	109	
45	Min	30	39	39	49	45	61	
46								

Figure 3. A typical spreadsheet. This is an example of a simple spreadsheet used to keep track of grades for a class. Spreadsheets are made up of rows (indicated by numbers on the left) and columns (indicated by letters across the top). The intersections of rows and columns are called “cells,” which are designated by their column letter and row number. The active cell in this example, “F2,” is highlighted with dark borders and by the designation in the upper left-hand corner. Cells may contain either “constants” (such as “ALFRED” or “59”), or “formulas” that compute values based on other cells. In this picture, cell F2 contains the formula shown in the window at the top: “=AVERAGE(B2:E2)”. The value displayed in cell F2 is the average of ALFRED’s scores on the two exams, lab practical, and final exam (constants stored in cells B2, C2, D2, and E2). Similarly, special functions in cells at the bottom of each score column compute average, standard deviation, and maximum and minimum scores for each of the graded exercises in the course. More complex formulas allow the instructor to compare adjusted numeric averages to cutoff values for letter grades and place letter grades for each student into column H.

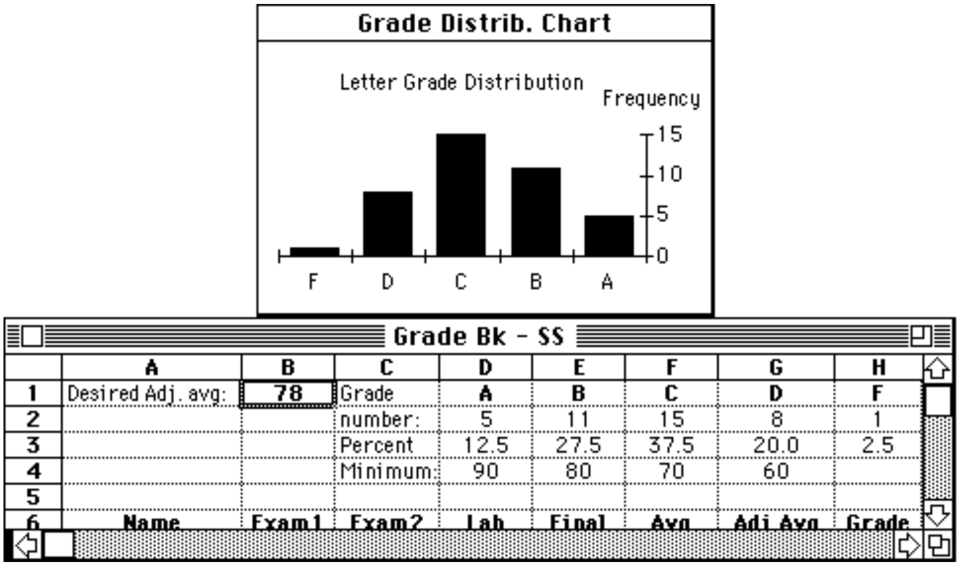
In Figure 4, the top of the spreadsheet has been modified to let the instructor set a desired class average of 80 and minimum scores for each letter grade. The values in cells D2 through H2 reflect the letter grades that result from those values. The chart reflects the same values, but shows more clearly that there were fewer D's than one might expect in a truly bell-shaped distribution. Changing the number in cell B1 (the desired overall class average) would result in Figure 5.



	A	B	C	D	E	F	G	H
1	Desired Adj. avg:	80	Grade	A	B	C	D	F
2			number:	6	12	18	4	0
3			Percent	15.0	30.0	45.0	10.0	0.0
4			Minimum:	90	80	70	60	
5								
6	Name	Exam1	Exam2	Lab	Final	Avg	Adj Avg	Grade

Figure 4. Modified spreadsheet with chart. This is a modification of the spreadsheet in Figure 3. Five rows have been added at the top, along with a summary table showing distribution of letter grades by number of students and percent of class To facilitate "curving," a desired adjusted average for the class has been put into cell B1, and cutoff scores for each letter grade have been placed into cells D4 through G4. The minimum values for letter grades and desired class average are linked to the cells containing adjusted averages and letter grades for each student; changing any minimum or the desired average would change appropriate student averages and grades. A chart has been added above the spreadsheet that is linked to the values in the spreadsheet containing the number of each letter grade.

The grade distribution in Figure 5 looks much more like the classic bell-shaped curve and might be more acceptable to the instructor. The point here is that doing comparable work with paper and pencil would have required far more work than with a spreadsheet. Importantly, the instructor would almost inevitably have had less time to really think about the grades (or other important work).



	A	B	C	D	E	F	G	H
1	Desired Adj. avg:	78	Grade	A	B	C	D	F
2			number:	5	11	15	8	1
3			Percent	12.5	27.5	37.5	20.0	2.5
4			Minimum:	90	80	70	60	
5								
6	Name	Exam1	Exam2	Lab	Final	Avg	Adj Avg	Grade

Figure 5. New chart following a change in the spreadsheet Changing the value for the desired class average (cell B1) from 80 (Figure 4) to 78 immediately changes the summary table and the chart to reflect the revised letter grades.

Data Base Packages

The essence of data base software is that it lets people store lots of different sorts of information and then extract, sort, and summarize that information in a great many ways. While spreadsheets and statistics packages can do some of these operations, they work best with numeric information that can be put into narrow columns, and are less practical for textual information and for complex searches and printed output. A bibliography is a good example. A researcher may not remember where she read something, but does remember that it was in a copy of an article in the journal Nature within the last 2 years and the author was “Smith,” “Smyth,” or “Smithson.” If she has entered all of her reprints into a database, she could find the reference very quickly.

It is significant that a bibliography is heavily textual, cannot be practically arranged in columns and rows, and will be added to over a lengthy period of time. Any research program evolves over time, so it is important that a researcher or team be able to restructure a collection of data so that it can be used to answer new questions (and old ones in new ways). In the example of the class grade book above, a spreadsheet was ideal. Suppose, however, the faculty member (perhaps a department chair) wanted to track students (advisees, majors) through their undergraduate years and even after graduation?

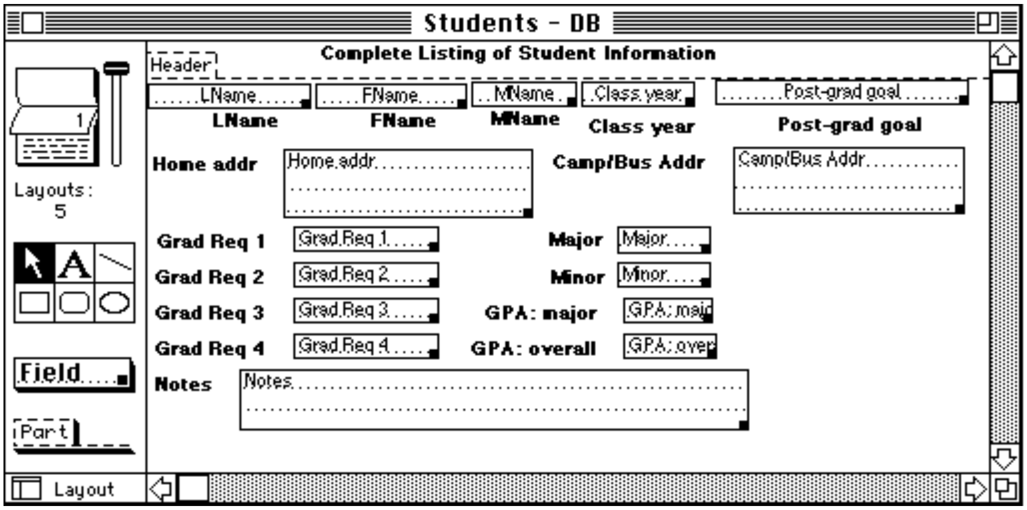
What are some of the items of information that might be useful? Some items that come to mind include: Name, birth date; home and campus addresses; class year; major;

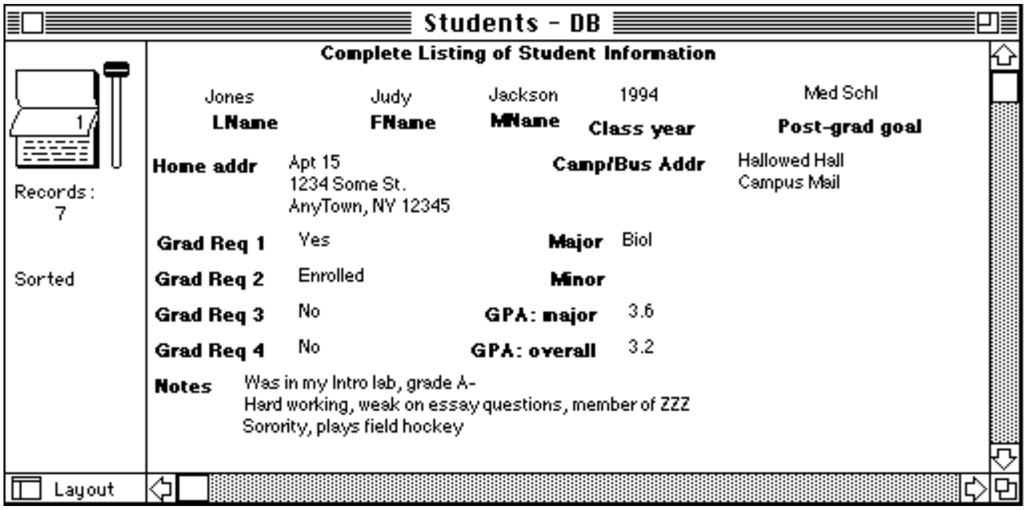
completion status of graduation requirements; grade point average; anticipated career; and notes from meetings and conversations. Information about graduated students might include job and home addresses; graduate schools, degrees and dates; information about spouse and children, etc.

How might the information be used? Some possibilities include: lists of advisees to receive notes about advising appointments; list of seniors to receive invitations to a department party; complete printout of all information on graduated seniors for department files; summary report of grade point averages of all students who applied to medical school compared with those who were accepted and rejected; and list of seniors who have not yet completed graduation requirements.

The complete list of information that could be included in each student's record might be rather lengthy. The professor would usually need only some of that information at any time, and would want to produce a variety of reports and summaries at different times. This is exactly the situation where a data base would be useful. Figures 6 through 8 provide examples of reports from such a database.

Figure 6 illustrates the complete record with all of the variables (often called "fields" in data base terminology) for one hypothetical student. It would be difficult to lay out this information in a spreadsheet. The flexible formatting of a data base allows variable names to be shown here in boldface and arranged below or beside the values for this student in any order or place on the "paper." In this case, the author of the report chose to put first, last, and middle names into three fields; this provides flexibility -- some reports may print last name first, others (such as a greeting in a letter) may use just the first name. Many data bases will split one address into multiple fields (street, city, state, zip code) to allow for sorting by zip code or state. The author of this data base decided that was not needed and provided only two address fields.


6a -


6b. -

Complete Listing of Student Information

LName: Jones
FName: Judy
MName: Jackson
Class year: 1994
Post-grad goal: Med Schl

Home addr:
Apt 15
1234 Some St.
AnyTown, NY 12345

Camp/Bus Addr:
Hallowed Hall
Campus Mail

Grad Req 1: Yes
Grad Req 2: Enrolled
Grad Req 3: No
Grad Req 4: No
Major: Biol
Minor:
GPA: major: 3.6
GPA: overall: 3.2

Notes:
Was in my Intro lab, grade A-
Hard working, weak on essay questions, member of ZZZ
Sorority, plays field hockey

Records:
7

Sorted

Figure 6. Complete data base record on one student. An example of a data set more suited to a data base than a spreadsheet. Figure 6a is a “layout” that determines the arrangement and identity of items to be displayed from the data base. Figure 6b illustrates a hypothetical record for one student. The person constructing the layout has almost total control over the arrangement and formatting of the report. The left side of the figure contains the idiosyncratic controls for this particular data base: a picture of a book that shows this is the first record. Clicking on the top or bottom pages move to the previous or next records The “slider” can be dragged with the mouse to move more than one record at a time. The display also shows that there are seven records in the data set and they have been sorted.

Not all of the information needs to be displayed at one time, and often it is useful to put only a subset of information in any one layout. Figure 7 illustrates one such situation: a mailing label.

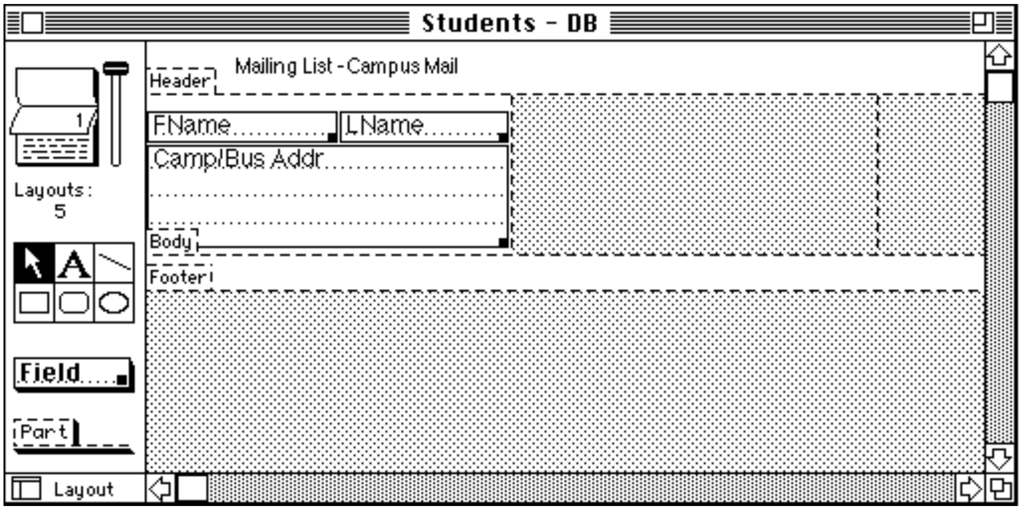
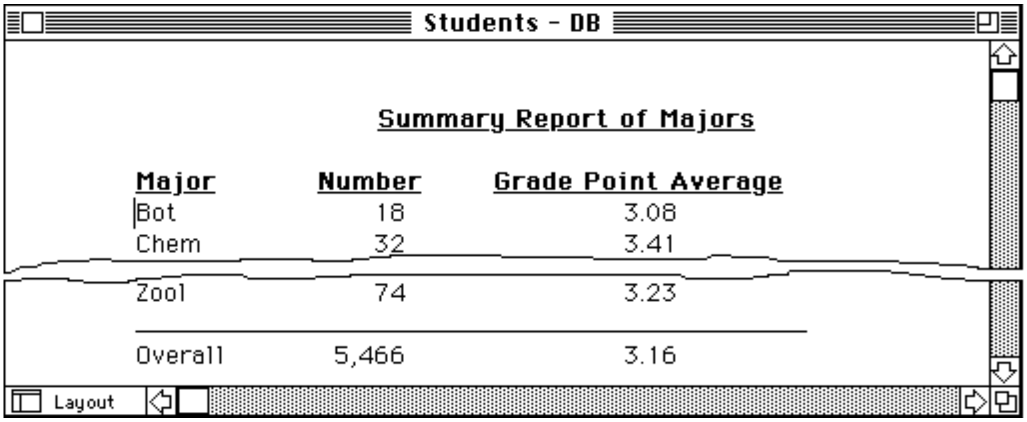


Figure 7. Mailing label from data base. In this instance, no variable names are printed, just the information in three fields. The gray area beside the name and campus/business address show where two other records will be printed. This layout is designed to print 3 labels across a page.

Most data bases provide very flexible tools for printing such things as mailing labels. They also provide ways of "printing" fields to a file on a computer disk that can be "mail merged" to print multiple letters. Fields such as first name can be inserted into proper places in a form letter and one "personalized" copy can be printed for each person in the data base. It's not visible in this figure, but all data bases allow you to select records based on a variety of criteria, such as students interested in medical school with grade point averages below 2.5.

A final example of the capabilities of a data base is shown in Figure 8: the ability to sort and summarize information.



Summary Report of Majors

Major	Number	Grade Point Average
Bot	18	3.08
Chem	32	3.41
Zool	74	3.23
Overall	5,466	3.16

Figure 8. Summary report from a data base. In this report from a large data base, the author wishes to determine the GPAs of students from a variety of departments. The individual students' information is not printed, only the number of students and the average GPA for all students in each major.

This brief discussion of data bases has covered only a few of their uses. As in the discussion of spreadsheets, there are many capabilities that we have omitted. Hopefully, you can see that a data base is a very powerful tool. People who get used to having one often find themselves building many different data bases and consider them second only to word processors in utility.

Refer once more to Figure 2. As with spreadsheets, scientists will enter information into data bases, then use it in a variety of ways. It can be sorted and summarized to clarify patterns in the data and help the researchers answer the questions they have posed. These patterns will often suggest revisions in the way the research is being done and new variables that should be studied, and in general help generate the results that produce manuscripts and enter into the feedback loops leading back up on the right of the flow chart.

As you might expect, data bases tend to grow and evolve over time. One scientist might start a project and develop his own data base. If it is useful, he will add to it over time and colleagues will begin to use and add to it. If the information is especially useful, the data base itself will be taken over by a professional organization and take on a life of its own to become a sort of publication or tool in and of itself. This possibility is suggested by the line leading from the data base circle down to the “Published results” box in Figure 2. An important current example is the proposed “human genome” project, but there are many others ranging from collections of infrared and other spectrograms to records of Christmas bird counts, bird banding records, human census records, climate and weather data, scientific publications, and many others. Importantly, many of these collections of data can be regarded as resources than can be mined in ways that their creators never imagined. Christmas bird counts were started at the beginning of this century by amateur birders, and their results published each year. The records were finally put into computers and used to study long-term population trends and many other ornithological and ecological phenomena.

Bibliographic Data Bases

One additional type of data base is of special significance: bibliographic data bases. Keeping track of the enormous volume of existing knowledge is an increasing challenge. Information that is not public is not a part of science and no one can pretend to be a scientist without doing their reading. Bibliographic information is rather different from other collections of data because there are so many different types of “publications”: journal articles, books, series, government reports, maps, films, and conference proceedings are just a few. Each type of publication has different information that must be noted (different database fields), and they are cited in different ways -- there is no single record layout that covers all of the possibilities.

Not surprisingly, there are a number of specialized bibliographic data bases to help with the job. In keeping with the theme of the previous paragraph, bibliographic data bases often can take records from giant commercial data services. From there, scientists use the information in preparing manuscripts and in defining the research problems they wish to work on. These relationships are shown in Figure 2 by the arrows from Prevailing paradigms and Published results to the Bibliographic data base circle and from that to Questions and Word Processing.

Statistics Packages

Statistical computations are an obvious use of computers, and statistical packages were among the earliest written for computers. Older, “mainframe” computer packages were difficult to learn and use, but the newer microcomputer packages are far easier and in some ways more versatile. While spreadsheets can do many statistical calculations, if you need to do complex statistics and related graphs and charts, then you need a stat package. Again, this is a topic for another module. If you start off working with a spreadsheet and decide later that you should have used a stat package, don’t worry. Statistics packages can easily exchange data, both tabular and graphic, with other programs like spreadsheets, word processors, and data bases.

Data Graphics and Other Graphics Programs

Most spreadsheets, data bases, and stat packages don’t produce quite the images that are needed either for the analysis or for the persuasion phases of a research project. Two types of programs that can remedy this situation are grouped here as graphics and data graphics.

Data graphics programs allow you to import data from a variety of sources, often into a spreadsheet-like table, and then to produce a wide variety of standard scientific plots, charts, and graphs. These programs allow very specific control over such things as type of graph, axis scale and range, and labeling, and follow most scientific conventions. A new type of data graphic program allows you to store a map, along with data about subregions of the map. These programs can be used to color in parts of the map that have certain attributes, such as all of the collecting localities where a certain species of plant was collected.

Regular graphics programs can import images from other programs, as well as scanners and video cameras, and edit them to produce figures suitable for publication and projection at seminars. Almost any Macintosh screen image can be moved into a graphic program for editing and inclusion into a word processor document.

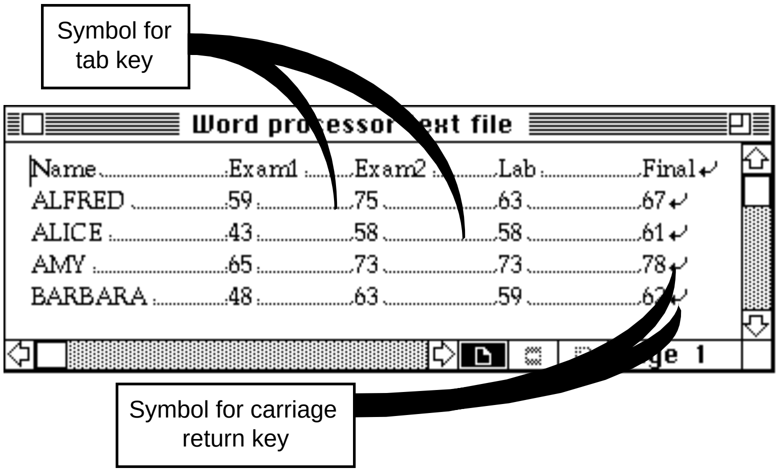
Word Processors

The role of word processing in the persuasion phase of BioQUEST is easy to see. Unfortunately, most people do not look at word processors as much more than typewriters with memories, though they are far more than that. For example, they can store notes and other information to serve as simple textual data bases. Note files can be searched with the word processor's find or search command, and information cut and pasted into another manuscript. In addition, word processors can be useful as tools to manipulate a variety of files to be converted from one form to another. To understand this, you need a little background.

It is important to realize that the majority of word processors store hidden codes along with the actual letters. These hidden codes determine, for example, where underlines begin and end, where carriage returns are located, and where fonts change. You normally can't see these nonprinting codes except by their effect on the appearance of the text, although some word processors will allow you to reveal the codes (Figure 9a). Virtually all word processors, however, can save files without these formatting codes. Such "text-only" files usually have a different icon than files that contain the formatting information. It may seem strange <u>not</u> to use formatting in a text file, but it can be very useful.

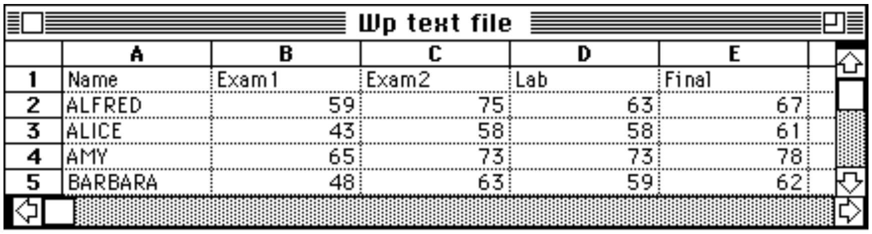
If you are using a spreadsheet and try to open a word processor file, you will not be able to see it in the normal open-file dialog box. However, most spreadsheets (as well as data base and statistics programs) <u>can</u> open text-only files. Some people like to enter numeric data into a table using their familiar word processor, then paste the table into a spreadsheet or statistical program. If they use the word processor to insert tabs between the columns of numbers, then each column will appear in a separate column of the spreadsheet. This is shown in Figure 9b.

Moving information around electronically opens many opportunities. If you have a table in a word processor and need to move columns and sort rows, consider cutting the table, pasting it into a spreadsheet where you can make the changes more easily. The modified table can then be cut and pasted back into the word processor.



Name	Exam1	Exam2	Lab	Final
ALFRED	59	75	63	67
ALICE	43	58	58	61
AMY	65	73	73	78
BARBARA	48	63	59	62

9a. -



	A	B	C	D	E
1	Name	Exam1	Exam2	Lab	Final
2	ALFRED	59	75	63	67
3	ALICE	43	58	58	61
4	AMY	65	73	73	78
5	BARBARA	48	63	59	62

9b. -

Figure 9. A word processor table saved as "text," then opened with a spreadsheet. The word processor used to create Figure 9a uses dotted lines to indicate where the tab key was pressed, and an arrow to show carriage returns. Note that spaces cannot be used to space columns; tabs are essential. The table was saved as "text only" and then opened directly with the spreadsheet. Figure 9b shows the spreadsheet that resulted before any formatting of text or columns was done. This was the approach used to start the spreadsheet in Figures 3-5.

Summary

We hope you now have some understanding of the variety of tools that are available for collecting and organizing scientific information. You will find that a good understanding of one of each of the basic, generic software tools -- word processor, data base, spreadsheet, statistics package, and graphics program -- will increase your ability to collate, organize, and display your data so that you can see the patterns in them, and persuade your colleagues of the value of your insights.

Too few people really look at computer software as modular toolkits and mix-and-match those tools in efficient ways. For example, this chapter was done entirely by computer and involved using the following software tools:

Software Type	Product Used	Used For
Spreadsheet:	Excel™	spreadsheet examples
Data Base:	FileMaker™	data base examples
Outliner:	More™	brainstorm chapter & initial writing
Statistics:	JMP™	statistics examples
Flow-chart:	MacFlow™	block charts of scientific process
Graphics:	SuperPaint™	editing of screen dumps
Scanner:	AppleScan™	digitize embryo & other pictures
Communications:	VersaTerm™	down-load data from mainframe
Word processors:	WriteNow™	author's favorite word processor
	MicrosoftWord™	word processor used by BioQUEST

All windows were captured as screen dumps using the standard Macintosh command-shift-3 sequence. The resulting MacPaint-format files were imported into a graphics program for minor editing, scaled down 75%, and pasted into the outline. Except for the hypothetical student database, all data were imported from existing sources (word processor, spreadsheet, stat package, or database) and exported to the other programs.

For example, the student grades used in Figures 3-5 are actual data (first names and scores) entered into a mainframe statistics package years ago. It required less than 20 minutes with five programs to produce Figure 3: down-load the data from mainframe to microcomputer with a communications program; open the file with a word processor, replace commas between last and first names with tabs using one global replacement command, save text-only file; import the data into spreadsheet, delete the column of last names, sort by first name, add row and column statistics, store screen image, save spreadsheet file; open screen dump with graphics program, remove extraneous material, save graphics file, copy image; open word processor file and paste. Figure 4 required 15 minutes: 10 to modify the spreadsheet and create the linked chart and 5 to convert to a picture in the word processor. Figure 5 took less than 5 minutes.

In the next sections, we will look at a number of examples that illustrate some practical “tips and tricks” for organizing data, and give you an opportunity to organize some of your own.

An Embryological Example with Tips and Tricks

Now that you have some background, we will take you through an example of how one researcher modified her research program to take advantage of opportunities provided by computer software.

A basic question about embryos that is surprisingly poorly known is, how rapidly are cells proliferating (dividing) in different parts of an embryo at different times? A related issue is, what proportion of various cell populations are dividing at any point in time?

One way to address these questions is to bathe embryos in a solution containing DNA components that are radioactive -- dividing cells will take up the radioactive label. After a period of time, the embryos are removed, preserved, cut into thin sections, and placed on slides (Figure 10). The slides are coated with photographic emulsion and left for a period of time, and then the emulsion is developed. Finally, the slides are stained and covered. When examined under a microscope, cell nuclei that were synthesizing DNA and getting ready to divide have many dots over them -- silver grains in the emulsion exposed by the radioactivity. Counting the number of labeled and unlabeled nuclei allows a researcher to calculate a *proliferation index*, the percentage of cells that are dividing.

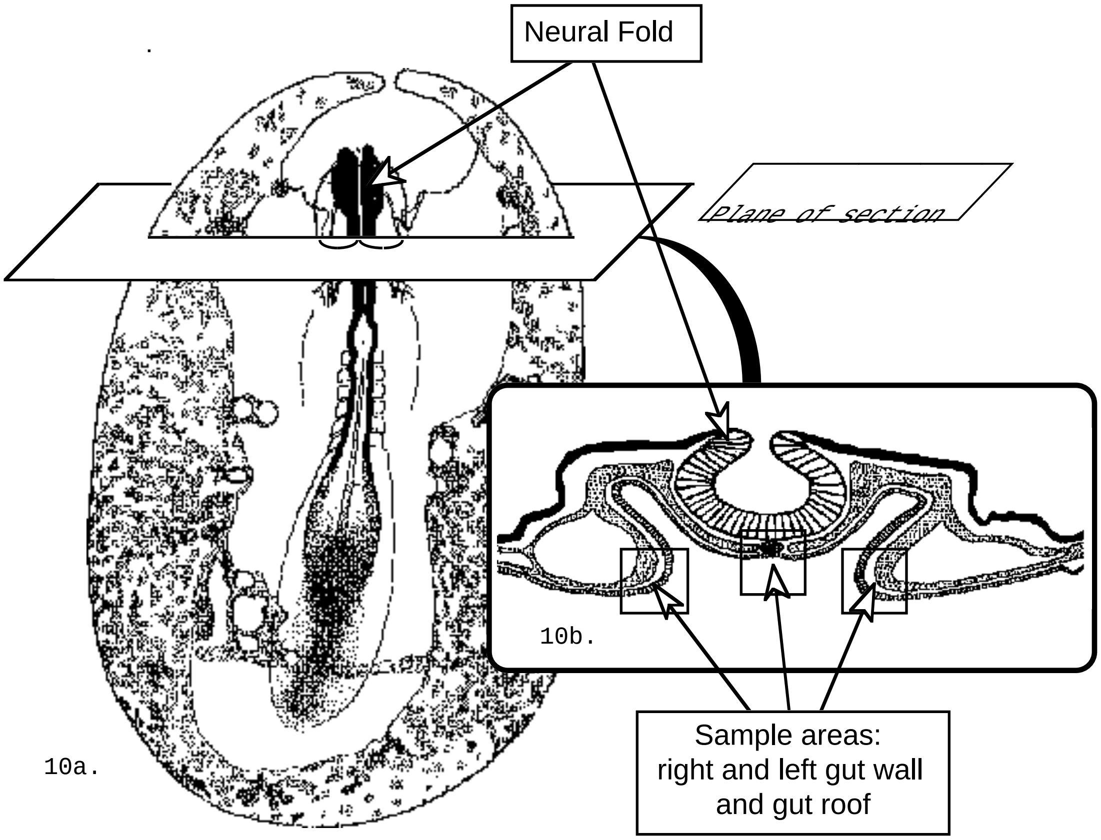
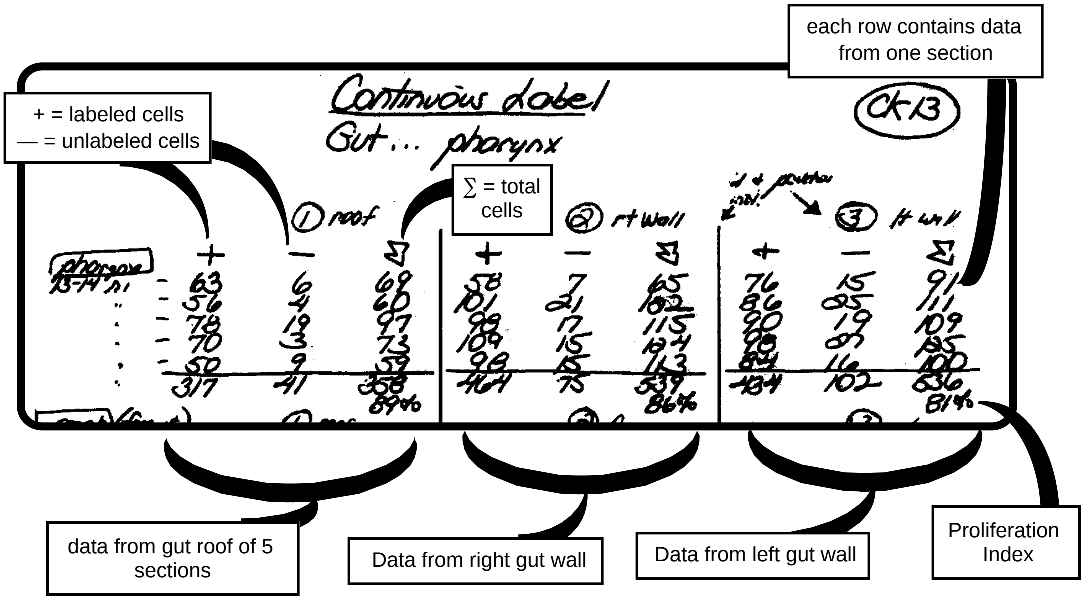


Figure 10. Sectioning a chick embryo. Early chick embryos are basically flat discs sitting on top of a ball of yolk. Figure 10a shows the disk with a plane showing how it was cut. Figure 10b shows a typical section, and the arrow points to a typical sample area where labeled and unlabeled cells would be counted. Labeled and unlabeled nuclei would be counted in each square area.

The labeled and unlabeled cells are counted using a microscope eyepiece that has a fine grid etched in it. The grid is placed over a part of the embryo at low power (where silver grains can't be seen) to avoid bias in sample choice. A hand counter with two buttons is used, one to count labeled cells and the other for unlabeled. As you might guess, a scientist doing this sort of research will produce a large volume of data to analyze. Figure 11 shows a typical, traditional way of recording such data.



① roof +	① roof —	① roof Σ	② rt wall +	② rt wall —	② rt wall Σ	③ lt wall +	③ lt wall —	③ lt wall Σ
63	6	69	58	7	65	76	15	91
56	4	60	101	21	122	86	25	111
78	19	97	98	17	115	90	19	109
70	3	73	109	15	124	98	27	125
50	9	59	98	15	113	84	16	100
317	41	358	464	75	539	434	102	536
		89%			86%			81%

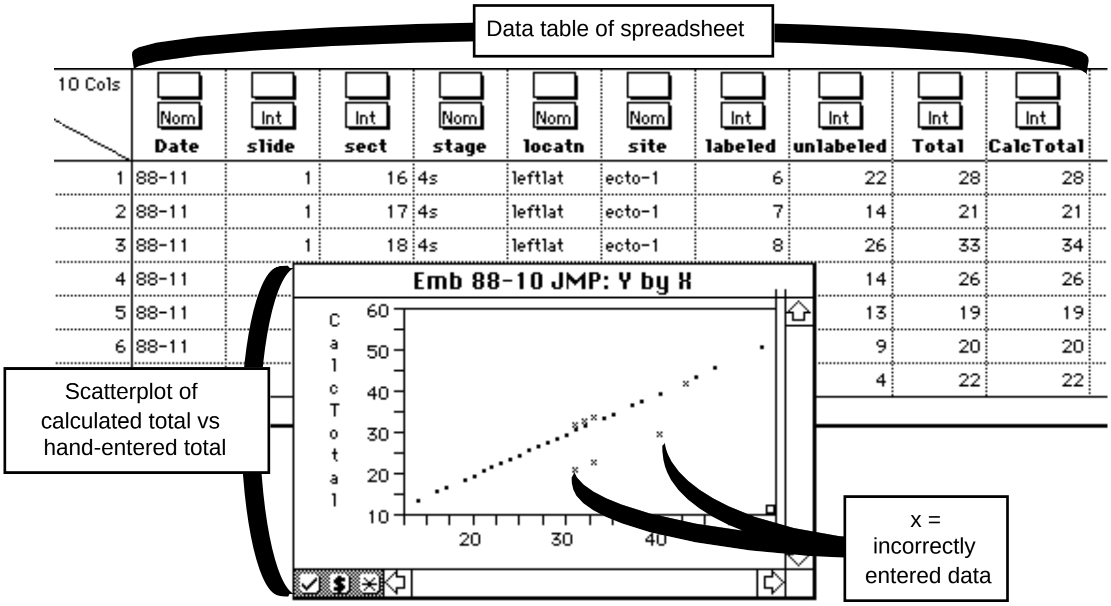
Figure 11. Part of a typical, traditional data sheet for one embryo. The top of the page shows the embryo number (Ck13) and the general region being sampled (pharynx); on the left below the rectangle is the number of the slide from which the data were taken. The five rows show data from five sections like the one in Figure 10b; they are in three groups because there were 3 sample areas on each section. Data from one sample area were added together to get the total number of cells, then the number labeled were divided by the total and multiplied by 100 to get the proliferation index.

Consider the difficulty of making use of data such as these. Handwriting is sometimes hard to read; the 10 numbers in each sample area (for example, the gut roof) must be added up and the number labeled must be divided by the sum to produce the proliferation index for the sample area. Once this is done for one embryo, other embryos must be sampled. Data from several embryos at the same stage of development must be pooled together. Finally, the real analysis begins -- data from various tissue layers and regions of the embryo need to be grouped and compared statistically to find significant differences and results need to be displayed in meaningful ways. Clearly the data management problems seriously complicate the process of analysis.

If you were to make this research easier, what would you do? Think of the software tools you know about, what information you would enter, and how you would organize them.

How to Collect and Organize Data from Individual Embryos

A statistics package seemed like a good choice. To try out this approach and learn to use the software, the researcher took some previously collected data and typed them in, with results shown in Figure 12. The data were entered into a data table that looks much like a spreadsheet. The researcher entered all of the available data, including total cells per sample and proliferation index. She then added new columns in which the program computed total cells and proliferation index.


Data table of spreadsheet

10 Cols	Date	slide	sect	stage	locatn	site	labeled	unlabeled	Total	CalcTotal
	Nom	Int	Int	Nom	Nom	Nom	Int	Int	Int	Int
1	88-11	1	16	4s	leftlat	ecto-1	6	22	28	28
2	88-11	1	17	4s	leftlat	ecto-1	7	14	21	21
3	88-11	1	18	4s	leftlat	ecto-1	8	26	33	34
4	88-11							14	26	26
5	88-11							13	19	19
6	88-11							9	20	20
								4	22	22

Scatterplot of calculated total vs hand-entered total

x = incorrectly entered data

Figure 12. Preliminary data entered into statistical package. Data from over 500 sites in one embryo were entered into a stat package. Several columns are not shown. The column labeled “Total” was hand-calculated; “CalcTotal” was computed as “Labeled+Unlabeled” by the statistics package. Plotting the two totals should have produced a straight line, but seven points (marked by x) indicated data entry errors (some are a little hard to see here because the scale is small -- on a full screen they are clear).

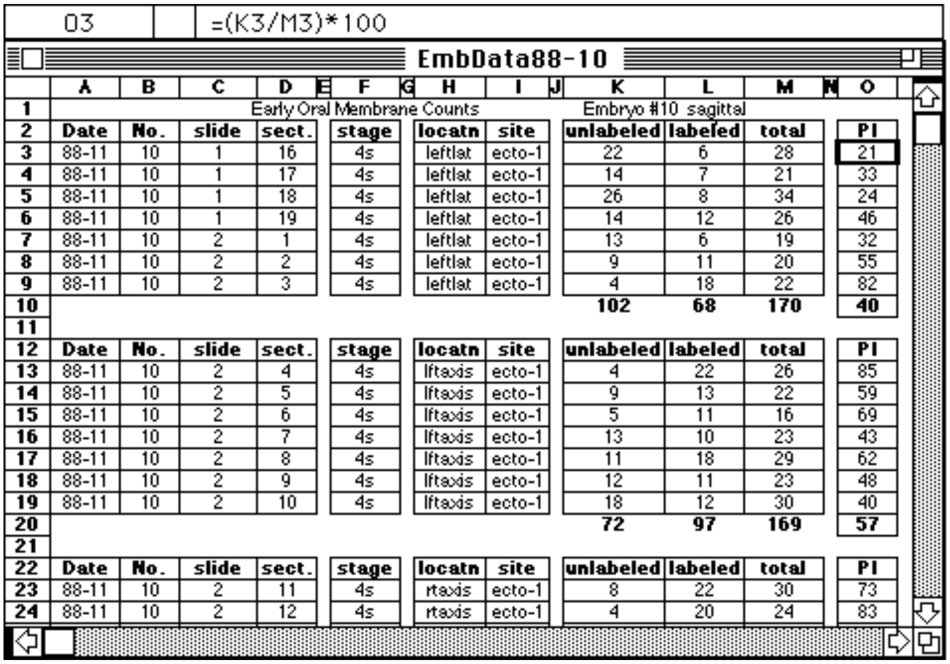
This preliminary exercise revealed a number of useful things:

- Data entry with this particular package was rather tedious: repetitive data, such as Date, had to be typed into each line. There was no command comparable to “fill-down” in a spreadsheet.
- It is essential to enter enough information into each row that proofreading data is easy. Section number (Sect) had not been entered into the initial data table. It was very tedious to go back to check the data against the paper copy -- data in some rows were mixed up, and reconstructing the error was time-consuming without the section number.

- The researcher didn't like editing data that were in one big table; she preferred to work with smaller chunks of data like those shown in Figure 11.
- Like many new computer users, she tended to not trust the machine. In this case, she entered values calculated by hand when the software could do the work automatically. A number of errors crept into the manual calculations and as the data were entered. It is much easier and more accurate to enter (and check) just the minimum data, then let the computer compute derived data.
- It's always a good idea to verify formulas with manual calculations. She made mistakes learning the program and her first formula had a mistake that resulted in erroneous results.
- It is important to do simple scatterplots, histograms, and other descriptive plots to check the validity of the data. A little "playing" with the data revealed the formula error mentioned above, and that there were hidden errors in the manual totals (and in the manually computed proliferation index), as shown in the scatterplot in Figure 12.

Despite the advantages of quick, accurate computations and graphing, the researcher did not like the data entry and felt that proofreading and editing the data were more difficult than before she used the computer.

To facilitate data entry, the researcher decided to try using a spreadsheet for data entry and initial validation. The initial result is shown in Figure 13.



O3 =(K3/M3)*100

EmbData88-10

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1						Early Oral Membrane Counts					Embryo #10 sagittal				
2	Date	No.	slide	sect.		stage		locatn	site		unlabeled	labeled	total		PI
3	88-11	10	1	16		4s		leftlat	ecto-1		22	6	28		21
4	88-11	10	1	17		4s		leftlat	ecto-1		14	7	21		33
5	88-11	10	1	18		4s		leftlat	ecto-1		26	8	34		24
6	88-11	10	1	19		4s		leftlat	ecto-1		14	12	26		46
7	88-11	10	2	1		4s		leftlat	ecto-1		13	6	19		32
8	88-11	10	2	2		4s		leftlat	ecto-1		9	11	20		55
9	88-11	10	2	3		4s		leftlat	ecto-1		4	18	22		82
10											**102**	**68**	**170**		**40**
11															
12	Date	No.	slide	sect.		stage		locatn	site		unlabeled	labeled	total		PI
13	88-11	10	2	4		4s		lftaxis	ecto-1		4	22	26		85
14	88-11	10	2	5		4s		lftaxis	ecto-1		9	13	22		59
15	88-11	10	2	6		4s		lftaxis	ecto-1		5	11	16		69
16	88-11	10	2	7		4s		lftaxis	ecto-1		13	10	23		43
17	88-11	10	2	8		4s		lftaxis	ecto-1		11	18	29		62
18	88-11	10	2	9		4s		lftaxis	ecto-1		12	11	23		48
19	88-11	10	2	10		4s		lftaxis	ecto-1		18	12	30		40
20											**72**	**97**	**169**		**57**
21															
22	Date	No.	slide	sect.		stage		locatn	site		unlabeled	labeled	total		PI
23	88-11	10	2	11		4s		rtaxis	ecto-1		8	22	30		73
24	88-11	10	2	12		4s		rtaxis	ecto-1		4	20	24		83

Figure 13. Using a spreadsheet for data entry. Numbers of unlabeled and labeled cells from each sample site were entered into a section of the spreadsheet and formulas to compute summary totals and proliferation indices. The "fill-down" command was used to enter repetitive data in columns such as Date, Locatn, and Site. Formatting the display with blank space between sample sites made printed copies easier to read.

This approach to data entry and proofreading was much more satisfactory. Repetitive data could be entered once, then copied down columns. Data from one sample area could be viewed as a whole. Blank space between sample areas made the data easier to read and proof. It was relatively easy to import the data into the statistical package, remove the blank lines between sample sites, and save the final data set.

Once the data had been moved back to the statistics program, additional analyses could be done. Figure 14 shows one of the plots that showed significant variation in rates of cell division along the length of the embryo. A number of unusually high or low rates of division have been marked with X's. On closer examination, these turned out to be caused by mix-ups in copying data from counters to spreadsheet. For years, the scientist had pushed the left-hand button for labeled cells and the right-hand button for unlabeled cells. Note that the columns in Figure 13 have the Unlabeled column to the left of the Labeled. The researcher had reversed the order when building the spreadsheet. This transposition lead to a number of data-entry errors because left-right data on the counter had to be recorded in right-left spreadsheet columns. When she forgot to change the order, the computer proliferation rates were inverted -- high rates became low and vice versa.

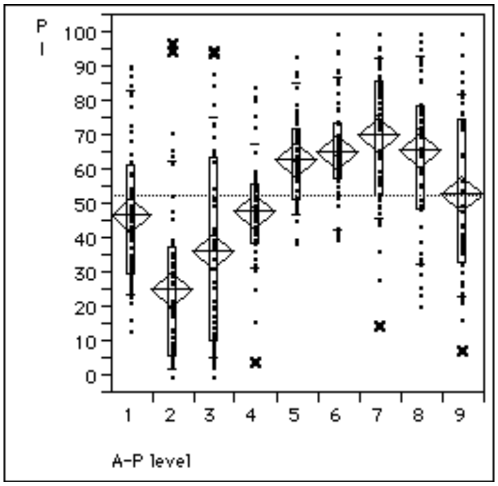


Figure 14. Initial plot of proliferation index vs anterior-posterior level. The horizontal axis shows how proliferation index ("PI," percent of cells dividing) varies from the front of the embryo (level 1) to the posterior (level 9). The clear pattern of low division rates in the front and high rates in back is very clear. Note that a number of extremely high or low proliferation indices seem to reverse the pattern in their columns; these data point have been marked with x's.

Fortunately, the spreadsheet columns could be reversed in a few seconds so that subsequent data could be entered with fewer errors. This sort of consistency is important. Here again, the computer made life easier. If the data had been written onto paper, rewriting them to transpose columns would have been a real chore (and would have almost certainly introduced additional copy errors).

How To Collect and Organize Information About Whole Embryos

All of the previous discussion concerned information about individual embryos and demonstrated that a good deal of thought and work can go into managing that sort of information. Now consider a larger issue: how to organize information about whole embryos.

Any research program grows and changes over time. As you will notice in your own work in BioQUEST, answers to questions in turn pose additional problems. Information not considered important at one time may become important later. Our embryologist was at one time concerned with effects of a drug on cell proliferation. In the course of that project, she noticed differences between the left and right sides of the embryos. She began to wonder if these were related to the process by which vertebrate embryos rotate onto their left sides and collected data related to that question. Results from that project suggested it would be worth looking at structures, like the gut tube, that resulted from folding of layers of cells.

So far, she and her students have sectioned and prepared almost 400 embryos. Of the 30-odd embryos in any experimental group, only 20 or so would meet the criteria for inclusion in the current project. Some of the other embryos were too old or young for a current problem and weren't even sectioned (although they were saved). In other cases, specific structures might have been damaged in preparation. While not suited to one project, however, these rejected embryos might be just right for another project.

She began to wonder if there might be a good way to keep track of her collection of embryos. She needed a system that would allow her to find, for example, embryos of particular ages, or sectioned at a particular angle, or radioactively labeled during a particular stage of development. Now that you know something of the software tools available, how would you go about designing a system to meet this need? Note that the focus in this problem is on whole embryos, not on samples from within embryos. Rather than present a solution, we will (as they say) leave this as "an exercise for the student."

Summary

A number of other changes were made in the way data were collected and organized in this study, but this discussion will suffice for our purposes. Let's summarize some of the take-home lessons:

Easy, accurate data entry is important. Give careful thought to how you enter your data so that you can avoid "typos" and other data-entry mistakes such as the transposition of columns mentioned above. Even though our embryologist is a methodical and careful worker, some errors crept in. Although a dozen errors in almost 6000 data points might seem trivial, they often are not. Extreme values such as those marked with X's in Figure 14 can significantly distort many statistics. In some cases, this may mean entering data into a program that will not be used for the analysis. If you are comfortable with a program such as a spreadsheet or even a word processor, then that may be the best way for you to enter data. This is especially true given the next point.

Once data are in electronic form, they can be easily moved to another program. There is almost always a way to move data from one form (computer, disk, or software package) to any other form. In the embryology example, data could easily be moved from spreadsheet to stat package. It's almost always worth spending time learning how to convert data rather than reentering them by hand.

Enter enough information that data can be easily checked and corrected (e.g., an ID number). Each row of a data table should have enough information that the data can be checked against original sources. For some projects, this may be as simple as assigning a unique identifier number or name. In the embryology data, a combination of embryo number, slide number, and section number were needed.

Don’t enter unnecessary data; let the computer calculate derived variables. Look for ways to have the computer calculate variables. Computing derived variables by hand (or electronic calculator) is almost certain to introduce additional errors. Of the dozen-odd errors detected in the embryology example, seven were eliminated by having the computer do as many calculations as possible.

Check computer calculations by hand. Depending on your familiarity with a piece of software and how careful you are, mistakes can be made in setting up computations. Compute derived variables by hand for a few test observations so you can verify that the computer does what you thought you told it to do.

Be sure to put typical data through a sample analysis with all tools and procedures. You may find that a software package or procedure is not as good as you thought at first. Setting up a test with a small data set may save you a lot of grief later. This is especially true if you will need to convert data from one program to another.

Always explore your data in a variety of ways to validate your data. As the embryologist found out above, simple descriptive statistics and displays of pairs of variables can clearly pinpoint data entry errors and suggest ways to improve data organization.

Now You Try It

In this chapter we have looked at how computer software can be used to facilitate solving problems and to provide information and graphs for persuasion. You will have many opportunities to do this in BioQUEST. But rather than wait, we suggest that you work through an actual problem.

Your instructor may provide you with an opportunity of his or her choice, or let you choose a problem of your own. If not, consider the data set collected in 1898 and published in 1899 by Dr. Hermon Bumpus (Bumpus 1899). The paper also may be found in Bajema's more recent collection (Bajema 1983) as well as Appendix A. I suggest you read his paper, for it makes a fascinating contrast to current scientific publications. Not only does it not have the modern format but it lacks the standard statistical techniques that we have come to expect. Nevertheless, it has become a classic paper in evolutionary studies and is well worth examination.

Some brief background: in February, 1898, there was a severe winter storm with rain, sleet, and snow near Providence, RI. One hundred thirty six English sparrows were found freezing and brought to Dr. Bumpus' laboratory at Brown University. Of those, 72 survived and 64 died. Bumpus took advantage of the opportunity to study an episode of natural selection. He measured a number of characteristics of the birds and analyzed them to find differences between the survivors and those that perished. His general conclusion was that the sparrows were subjected to *stabilizing selection* -- birds that were markedly different from the average were more likely to have died. In Bumpus' quaint phrasing:

> "The process of selective elimination is most severe with extremely variable individuals, no matter in what direction the variations may occur. It is quite as dangerous to be conspicuously above a certain standard of organic excellence as it is to be conspicuously below the standard. It is the *type* that nature favors."

Bumpus seems to have expected his raw data to be useful to others, for he published them. Indeed, as statistical methods have improved, a number of scientists have reexamined his data (Harris 1911; Calhoun 1947; Grant 1972; Johnston, Niles et al. 1972; O'Donald 1973; Manly 1976; Manly 1985; Crespi and Bookstein 1989).

Bumpus' complete paper is reproduced in Appendix A[1] and your instructor may choose to distribute it to you. The actual data from Bumpus' Tables I through IIIa are

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[1] available on the BioQUEST CD-ROM in the file, "DC&O Append A - Bumpus' Paper"

also reproduced in Appendix B[2] without his superscripted notations and averages. Your instructor either may ask you to enter the data manually from Appendix A, or may make available electronic copies of Appendix B. The first alternative is a good exercise in data entry and verification, while the second allows you to proceed more quickly with organization and analysis. Your instructor may opt to have you do an initial analysis at this time, or wait until later in the course when you are studying evolution or statistics. Appendix C[3] contains a more lengthy discussion of the pedagogical value of Bumpus' paper and data set.

Your instructor may assign one or more variables to you or your team and ask that you use the statistical methods you know to verify Bumpus' conclusions. Before you do that, however, you will need to give some thought to how you wish to organize the data for analysis -- Bumpus' organization is not suited to modern methods. How you reorganize, enter, and verify your copy of his data is the point of the exercise.

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[2] available on the BioQUEST CD-ROM in the file, "DC&O Append B - Bumpus' Data"

[3] available on the BioQUEST CD-ROM in the file, "DC&O Append C - Inst Notes"

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Appendix A: Bumpus’ Paper

ELEVENTH LECTURE.

THE ELIMINATION OF THE UNFIT AS ILLUSTRATED BY THE INTRODUCED SPARROW, *PASSER DOMESTICUS*.

(A FOURTH CONTRIBUTION TO THE STUDY OF VARIATION .)

HERMON C. BUMPUS.

WE are so in the habit of referring carelessly to the process of natural selection, and of invoking its aid whenever some pet theory seems a little feeble, that we forget we are really using a hypothesis that still remains unproved, and that specific examples of the destruction of animals of known physical disability are very infrequent. Even if the theory of natural selection were as firmly established as Newton's theory of the attraction of gravity, scientific method would still require frequent examination of its claims, and scientific honesty should welcome such examination and insist on its thoroughness.

A possible instance of the operation of natural selection, through the process of the elimination of the unfit, was brought to our notice on February 1 of the present year (1898), when, after an uncommonly severe storm of snow, rain, and sleet, a number of English sparrows were brought to the Anatomical Laboratory of Brown University. Seventy–two of these birds revived; sixty–four perished; and it is the purpose of this lecture to show that the birds which perished, perished not through accident, but because they were physically disqualified, and that the birds which survived, survived because they possessed certain physical characters. These characters enabled them to withstand the intensity of this particular phase of selective elimination, and distinguish them from their more unfortunate companions. It will be convenient for us to arrange our material in the form of tests, as follows.

Test 1: Sex.—It will be noted by reference to the tables that of the *surviving* birds the males are much more numerous than the females. Of the former there are fifty–one (thirty–five adults and sixteen young), while of the latter there are only twenty-one. Among the birds which perished, the females are absolutely and relatively more numerous than they are among the birds which survived, although more than one–half (thirty–six out of sixty–four) of the unfortunate birds are males. Of course it may be that male birds are naturally more abundant than females, but the present question is not one of distribution of sex, but rather of distribution of fitness, and the inference is that the females are less competent to resist severe winter weather than are the males, for, while only 28% of the survivors are females, they constitute 43% of those that perished.

Test 2: Length — The first column of figures on the several tables gives, in millimeters, the lengths of the birds from the tip of the beak to the tip of the tail. An examination of the averages, printed at the bottom of each column, will prove particularly instructive. It will be noted on Tables I and I^a that the average length of the adult males which survived (159 mm.) is really less than that of the adult males which perished (**162** mm.)[4] Similar figures, 159 mm. and **162** mm. on Tables II and II^a, indicate the same relative lengths of the young males of the two groups. The average lengths of the females of the two groups, 157 mm. and **158** mm., Tables III and III^a, also indicate an excess in the average length of the birds which perished. The birds which perished, then, males or females, adult or young, are longer than those which endured, and we

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[4] The numbers printed in light type, both in the text and in the tables, refer to birds which survived; those printed in heavy type refer to birds which perished.

are justified in concluding that when nature selects, through the agency of winter storms of this particular kind of severity, those sparrows which are relatively short stand a better chance of surviving.

Test 3: Alar Extent.— Averages based on measurements from tip to tip of the extended wings fail to bring out any striking difference between the two classes of birds. Both have an indicated average of 2.45 mm., although, to be more exact, the birds which perished averaged **2.449**, while those that survived averaged 2.455, a difference too slight to be of material significance. This similarity of the two groups is not to be wondered at, since it is not to be expected that one eliminative agent will express itself in all possible anatomical features. Were the eliminative agent, for example, a severe northerly wind of protracted duration, the alar extent might then enter in as a factor of considerable selective value, and survivors would then have an alar extent materially different from that of the birds eliminated.

The alar extent of the females, corresponding with their smaller size, is less than that of the males.

Test 4: Weight.—Had I been called upon to express an opinion as to whether heavy or light birds would be more successful in resisting the severity of the February storm, I should have declared unhesitatingly in favor of the heavy birds. An examination of the third column of measurements, however, will show that the birds which survived invariably average less in weight than those which perished, and that among the males this difference amounts to more than a gram; that is, to about one twenty–fifth of the weight. The surviving birds of both sexes had an average weight of 25.2 grams, and those which succumbed had an average weight of **25.8** grams.

It may not be out of place to call attention here to certain objections which may be raised to the method which I have adopted, and to the conclusions thus far derived therefrom. One may claim that the greater relative number of females in the group of birds which perished vitiates the numerical result, since the females are of less stature than the males. But it will be noted that this objection answers itself, for the birds which perished are not shorter, but longer, than those which survived; and again, that the birds which perished, though having a disproportionate number of the lighter sex, nevertheless have an average weight considerably greater than that of the birds which survived. Moreover, comparing, in the two groups, adult males with adult males, young males with young males, and females with females, we find that the differences between the two classes of birds are expressed in these three smaller divisions, and I think we are justified in concluding that the differences are really significant.

The explanation that the birds which lived were those which sought, or at least enjoyed, better shelter cannot be entertained, for the storm was of long duration, and the birds were picked up, not in one locality, but in several localities; and, moreover, it is a fact that the survivors are *structurally different* from those which perished. If to these structural characters one desires to add also the intellectual character that the birds knew enough to go in out of the storm, the difference between the two groups becomes so much the greater.

Test 5: Length of Head.—A comparison of the average lengths of head, from the tip of the beak to the occiput, shows only a similarity between the survivors and those which perished, and indicates that under the present environmental conditions this feature is not sufficiently prominent to be expressed by this method of computation.

Test 6: Length of Humerus.—An examination of the fifth column of figures will show that the length of the arm bones of the birds which perished always averages less than that of the survivors. This difference is most conspicuous in the adult males, where the surviving birds have an average length of humerus of .738 of an inch, considerably more than that of their unfortunate companions, **.727**.

Here again I wish to emphasize the fact that these differences cannot be merely accidental, because they so often tend in the same direction. If among the survivors it is the proper thing for adult males to have a long humerus, then the young males have a long humerus, and the females follow the prevailing fashion with characteristic servitude. If a short humerus is an index of inferiority, all three groups of eliminated birds (adult males, young males, and females) bear this same mark of inferiority. This fact is the more striking since the averages are established on a relatively small number of birds, while usually in the statistical methods of the study of variation an abundance of material is necessary.

Test 7: Length of Femur.—An examination of the general averages on Tables III and III^{a} shows that the survivors possess longer thigh bones than do the birds which succumbed. The average length of femur in the former is .716 inch; in the latter **.709**. This difference in the averages cannot be ascribed to the large number of dead females, since the difference prevails also for both the adult and young males.

Test 8: Length of Tibio–Tarsus.—Measurement of the tibio-tarsus yields practically the same comparative data as the measurement of the upper bone of the leg, although in both groups of birds this bone in the females is considerably longer than in the adult males, notwithstanding that the females are smaller. This series of measurements agrees with the sixth, in that the young males have longer legs than the adult males.

Test 9.—Measurements across the skull, from the postorbital bone of one side to the postorbital bone of the other, are given in the eighth column, and are less satisfactory, perhaps, than those of other portions of the skeleton. The breadth of the cranium, as thus indicated, is somewhat less in the females than in the males. The averages denote that the birds which survived had wider heads than those which perished, but these averages are considerably influenced by data furnished by the young males. The irregularities in the subordinate groups induce me to place less confidence in these numerical results than in the results from measurements of other structures.

Test 10: Length of Sternum.—This test differs from other tests in that it relates to measurements in the longitudinal axis of the body. In the males the sternum is long, and in the females it is short. In the birds which survived it has a general average length of .845 inch; in those which perished it has a general average length of only **.834**.

I think these tests prove that there are fundamental differences between the birds which survived and those which perished. While the former are shorter and weigh less (i.e., are of smaller body), they have longer wing bones, longer legs, longer sternums, and greater brain capacity. These characters are in accordance with our ideas of physical fitness; their defective development is evidently a mark of inferiority, and we are justified in concluding that the birds so handicapped failed to pass one of Nature's rigorous tests and perished.

In an earlier lecture, on the “Variations and Mutations of the Introduced Sparrow,” facts were adduced which, it was claimed, were sufficient to show that the English sparrow, since its introduction into this country, has found life so easy that the operation of natural selection has been practically suspended, and that the American type consequently has become degenerate. No active agent had eliminated anomalies, and certain “freaks” had increased in number, until they had become over four times as numerous as in England.

When calling attention to the occurrence of these variations, and to the fact that they were an indication of the absence of an active eliminative factor, I little thought that within a few months I might witness the action of an eliminating factor that would test the structural qualifications of *all* the birds: destroy those which had departed unduly from the ideal type, and thus raise the general standard of excellence.

It will be recalled that, after the storm of February 1, one hundred and thirty–six birds were taken, and that, of these, seventy–two revived, while sixty–four failed to recover. But the fact that the birds which perished had in the *average* longer and larger bodies, and shorter head, wing, and leg bones, does not tell all the story of selective elimination.

Reference to the tables will show, not only that the longest bird perished, but also that the shortest bird perished. The longest bird was No. **33**, the shortest No. **40**. (In these and other cases of extreme departure from the mean, the exponent I is placed in the table beside the number of the bird.)

Again, if we examine the columns of figures which indicate the alar extent of the different birds, we find that both the bird with greatest spread of wings, No. **32**, and the one with least spread of wings, No. **52**, perished.

The heaviest bird, No. **23**, weighed 31 grams; it perished. The honors for lightness are evenly divided; No. 53, among the survivors, and No. **60**, among the eliminated, have the same weight, *viz*., 22.6 grams.

The bird (No. **55**) whose head was longest (measured from the tip of the beak to the occiput) suffered elimination. The extreme variant in the opposite direction (No. 9) survived.

The honors for the longest humerus, .780 mm., are divided, Nos. 6 and **44**. The bird with the shortest humerus, No. **21**, perished.

The longest femur was possessed by bird No. **55**, the shortest by No. **51**. The surviving birds represent both extremes of variation of the tibio–tarsus (Nos. 18 and 41). In respect to all other columns of measurements the survivors possess exclusively never more than one of the *extreme* forms.

Both extremes of variation in width of cranium (Nos. **55** and **52**) are found among the eliminated birds.

The longest sternum is found in one of the surviving birds (No. **15**), and it will be remembered that a long sternum was considered a mark of excellence. The shortest sternum (No. **52**) is found among the eliminated birds where the standard is low.

These extremes of variation are represented on Table IV, and by counting the dark numbers we find that eleven extreme positions (maximum or minimum) are occupied exclusively by the birds which perished, whereas the light numbers show that only five extreme positions are occupied by those which survived. In two cases (the minimum weight and the maximum length of humerus) the extreme positions are occupied alike by birds of both groups, and consequently I have left the spaces blank. In three cases two birds of the same group occupy the same extreme position, but the table is designed to indicate only the *extreme positions* and not the number of birds occupying them. The *number* of birds occupying these extreme positions is represented on the previous tables by the exponent 1, and if we count up these exponents, we shall find that among the surviving birds there are nine cases of this extreme type, whereas among the birds which perished there are fourteen cases. These numbers are the more impressive when one considers that, inasmuch as there are seventy–two of the former birds and only sixty–four of the latter, the chances for the occurrence of extreme variation are not equal in the two groups. The birds which perished are at a decided disadvantage because of their smaller representation, yet there are many more "freaks" among them than among the surviving birds.

If it is thought that the association of the larger number of *extreme* variants with the eliminated birds is merely a matter of accident, we will not stop to argue the matter, but will apply the same test to the birds that remain after these extreme examples have been removed. We find even after the removal of these twenty–three examples, that extreme examples of the second order, indicated by the exponent 2, show the same tendency to occur more frequently among the eliminated birds.

The longest birds now are 166 mm.; the shortest, 153 mm. Of the former, Nos. **22**, **24**, **28**, **32**, **35**, perished, and No. 18 survived; of the latter, Nos. **45** and **62** perished, and Nos. 35, 54, and 55 survived.

If we count the times that the exponent 2 occurs in the tables, we shall find that there are ten birds of extreme abnormality of this second grade which survived, while there are twenty of the same grade which perished.

These figures indicate that the amplitude of variation of the surviving birds is less than that of the birds which perished. Were we to attempt the arrangement of the data into curves of distribution, the curve representing the distribution before the storm would be found to have a broad base, whereas the curve representing the distribution after the storm would be found to have a narrow base, for the eliminative process concentrated its energy on the individuals which occupied extreme positions.

Lest there remain some doubt as to the importance of this eliminative process, and of its efficiency in exterminating extreme variants, let us examine our figures again and see whether the group of birds which has already contributed thirty–four of the extremes of variation has still an excess of variability.

If we count up the exponents (3) of this third order of variable individuals, we find that the birds which survive give eleven examples, whereas those which perished give twenty–one. — It appears unnecessary to carry our investigations further along this line, for our results point always in one direction.

Natural selection is most destructive of those birds which have departed most from the ideal type, and its activity raises the general standard of excellence by favoring those birds which approach the structural ideal.

Inasmuch as the variation in structure in the birds which perished tends to centre about certain individuals, as, for example, Nos. **45**, **52**, and **55**, it might be claimed that the accidental presence of a few of these extremely abnormal individuals in this group is what really makes all the difference. Let us see.

There are twenty–three birds among the seventy–two survivors whose measurements bear exponents of extreme variation, and there are twenty–four birds similarly distinguished among the sixty–four which perished. But none of the birds in the first group has more than three exceptional features, whereas several of the birds which perished have a considerably larger number of exceptional features: four, five, and in one case, No. **52**, even six.

Of the twenty–three survivors which bear exponents, nineteen have only one exceptional character, and it is not surprising, considering the high standard of excellence possessed by these birds as a whole, that a single unfavorable feature does not prove fatal. There are but ten of the eliminated birds which have only one exceptional character, and the fact that some are burdened with more than one is apparently the reason for their mortality.

In an earlier contribution to the Study of Variation I called attention to a coincidence which may have considerable significance. When specimens of *Necturus* varied in respect to any one feature, there was a tendency for such specimens to present other and not necessarily correlated variations. Stated in another way, instability in respect to any one feature is an index of general organic instability. A similar coincidence of variations occurs among the sparrows.

Of the one hundred and thirty–six birds, five (Nos. 3, 47, 70, **21**, **52**) had albino feathers. Like other abnormalities endured by the surviving birds, albinism in two out of the three cases is the only affliction. But among those that were eliminated, where albinism twice occurs, it affects in one case a bird marked by four other abnormalities (No. 21), and in the other a bird (No. **52**) already cursed by six abnormalities, the most miserable individual in the entire collection.

While we have shown that the birds which perished have certain average structural peculiarities which distinguish them from the survivors, and that the intensity of selective elimination has been felt most by birds of extreme structure, it remains to be shown that a *general instability* of structure is as characteristic of the birds which perished as a *general stability* of structure is characteristic of those which survived. If we had sufficient data, this fundamental difference in the two groups of birds might be indicated by curves of distribution, one curve narrow and elevated, showing that its components are closely crowded around an ideal mean, the other broad and low, showing that its components are relatively indifferent to any ideal. But in the absence of sufficient data to illustrate the differences in this manner, we can arrive at a numerical result equally instructive by another method.

Having determined the ideal means for the several characters in each group of birds, we can then find the distance that each individual departs from this ideal. By adding these degrees of departure in respect to the several characters, and dividing by the number of individuals, we shall have numbers which represent the *average* departures from the ideal means. These numbers will be large if the members of a group of birds show a general tendency towards *disregard* of the ideals, and they will be small if the birds tend to crowd around the ideals. If all the birds actually attain the ideals, the number will be zero. — This is simply following out the principle that one man at the end of a ten–foot lever can do as much work as ten men at the end of a one–foot lever. A bird removed ten units from the mean exerts the same divergent influence upon its group that ten birds would exercise if removed one unit.

The results of this test, numerically expressed in Table V, are most instructive. In every case but one the numbers indicating the average departure from the ideal mean are smaller for the birds which survived, and thus indicate a general tendency toward conservatism on the part of the survivors. In the single exceptional case the numbers are not very different, 32 and **31**. Granting this exception to the uniformity in the figures, it is exceedingly interesting to examine the series. In respect to length, the birds which perished had an average departure from the ideal mean expressed by the number **3.48**, while the average departure of the birds which survived was only 2.51, or, expressed in tabular form:

In	respect	to	length,			**8.48**	is	greater	than	2.51
"	"	"	alar extent,			**4.60**	"	"	"	4.20
"	"	"	weight,			**12.5**	"	"	"	1.09
"	"	"	length	of	head,	**5.64**	"	"	"	5.51.
"	"	"	"	"	humerus,	**20.1**	"	"	"	16.0.
"	"	"	"	"	femur,	**20.0**	"	"	"	14.0.
"	"	"	"	"	tibio–tarsus,	**38.8**	"	"	"	29.4
"	"	"	width	of	head,	**12**.	"	"	"	10., but
"	"	"	length	of	keel,	**31.**	"	less	"	32.

A series of eight consecutive cases like the above, all pointing in the same direction, can hardly be considered accidental.

To summarize:

(I) We have found that there are fundamental differences between the surviving birds and those eliminated, and we conclude that the birds which survived survived because they possessed certain structural characters, and that the birds which perished perished not through accident, but because they did not possess certain structural characters which would have enabled them to withstand the severity of the test imposed by nature; they were eliminated because they were unfit.

(2) The process of selective elimination is most severe with extremely variable individuals, no matter in what direction the variations may occur. It is quite as dangerous to be conspicuously above a certain standard of organic excellence as it is to be conspicuously below the standard. It is the *type* that nature favors.

(3) Disregard of structural qualifications finally produces a throng of degenerates, whose destruction will follow the arrival of adversity.

Table I.

Measurements of Thirty-five Males which Survived

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
1 ♂	154[3]	241	24.5	31.2	0.687	0.668	1.022[2]	0.587	0.830
2 ♂	160	252	26.9	30.8	0.736	0.709	1.180	0.602	0.841
3 ♂	155	243	26.9	30.6	0.733	0.704	1.151	0.602	0.846
4 ♂	154[3]	245	24.3	31.7	0.741	0.688	1.146	0.584	0.839
5 ♂	156	247	24.1	31.5	0.715	0.706	1.129	0.575	0.821
6 ♂	161	253	26.5	31.8	0.780[1]	0.743	1.144	0.607	0.893
7 ♂	157	251	24.6	31.1	0.741	0.736	1.153	0.610	0.862
8 ♂	159	247	24.2	31.4	0.728	0.718	1.126	0.609	0.793
9 ♂	158	247	23.6	29.8[1]	0.703	0.673	1.079	0.602	0.820
10 ♂	158	252	26.2	32.	0.749	0.739	1.153	0.614	0.857
11 ♂	160	252	26.2	32.	0.741	0.723	1.129	0.624	0.892
12 ♂	162	253	24.8	32.3	0.766	0.752	1.134	0.633	0.923[2]
13 ♂	161	243	25.4	31.8	0.721	0.722	1.126	0.597	0.891
14 ♂	160	250	23.7	29.8[1]	0.730	0.703	1.103	0.590	0.820
15 ♂	159	247	25.7	31.4	0.729	0.717	1.141	0.592	0.927[1]
16 ♂	158	253	25.7	31.9	0.743	0.699	1.150	0.600	0.860
17 ♂	159	247	26.5	31.6	0.733	0.714	1.155	0.611	0.923[2]
18 ♂	166[2]	253	26.7	32.5	0.767	0.765[2]	1.230[1]	0.600	0.878
19 ♂	159	247	23.9	31.4	0.752	0.723	1.113	0.602	0.825
20 ♂	160	248	24.7	31.3	0.752	0.737	1.176	0.603	0.803
21 ♂	161	252	28.	31.8	0.770[2]	0.731	1.190	0.590	0.885
22 ♂	163	251	27.9	31.9	0.769[3]	0.745	1.168	0.622	0.860
23 ♂	156	242	25.9	32.	0.723	0.711	1.116	0.609	0.886
24 ♂	165[3]	251	25.7	32.2	0.751	0.742	1.161	0.613	0.865
25 ♂	160	247	26.6	32.4	0.728	0.707	1.108	0.590	0.836
26 ♂	158	244	23.2[3]	31.6	0.730	0.713	1.142	0.585	0.888
27 ♂	160	242	25.7	31.6	0.709	0.705	1.124	0.620	0.788
28 ♂	157	245	26.3	32.2	0.741	0.726	1.143	0.595	0.850
29 ♂	159	244	24.3	31.5	0.723	0.698	1.107	0.615	0.847
30 ♂	160	253	26.7	32.1	0.739	0.714	1.117	0.592	0.864
31 ♂	158	245	24.9	31.4	0.726	0.703	1.119	0.580	0.854
32 ♂	161	247	23.8	31.4	0.735	0.694	1.101	0.602	0.789
33 ♂	160	247	24.6	32.3	0.756	0.745	1.135	0.607	0.905
34 ♂	160	247	27.	32.	0.755	0.736	1.174	0.631	0.873
35 ♂	153[2]	241	24.7	32.2	0.728	0.680	1.092	0.592	0.884
Average	159	247	25.4	31.6	.738	.716	1.135	.602	.857

Table Ia.

Measurements of Twenty-four Adult Males which Perished

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
1 ♂	**165[3]**	**249**	**26.5**	**31.**	**0.738**	**0.704**	**1.095**	**0.606**	**0.847**
2 ♂	**160**	**245**	**26.1**	**32.**	**0.736**	**0.709**	**1.109**	**0.611**	**0.842**
3 ♂	**161**	**249**	**25.6**	**32.3**	**0.743**	**0.718**	**1.128**	**0.602**	**0.828**
4 ♂	**162**	**246**	**25.9**	**32.3**	**0.738**	**0.709**	**1.135**	**0.607**	**0.869**
5 ♂	**163**	**250**	**25.5**	**32.5**	**0.752**	**0.731**	**1.197**	**0.623**	**0.888**
6 ♂	**162**	**247**	**27.6**	**31.8**	**0.731**	**0.719**	**1.113**	**0.597**	**0.869**
7 ♂	**163**	**246**	**25.8**	**31.4**	**0.689**	**0.662[3]**	**1.073**	**0.604**	**0.836**
8 ♂	**161**	**246**	**24.9**	**30.5**	**0.739**	**0.726**	**1.138**	**0.580**	**0.803**
9 ♂	**160**	**242**	**26.**	**31.**	**0.745**	**0.713**	**1.105**	**0.600**	**0.803**
10 ♂	**162**	**246**	**26.5**	**31.5**	**0.720**	**0.696**	**1.092**	**0.606**	**0.809**
11 ♂	**160**	**249**	**26.**	**31.4**	**0.726**	**0.689**	**1.097**	**0.602**	**0.850**
12 ♂	**161**	**250**	**27.1**	**31.6**	**0.737**	**0.711**	**1.120**	**0.631**	**0.852**
13 ♂	**162**	**248**	**25.1**	**31.9**	**0.744**	**0.722**	**1.154**	**0.591**	**0.839**
14 ♂	**165[3]**	**252**	**26.**	**32.3**	**0.726**	**0.710**	**1.145**	**0.609**	**0.887**
15 ♂	**161**	**243**	**25.6**	**32.5**	**0.709**	**0.707**	**1.122**	**0.607**	**0.832**
16 ♂	**161**	**244**	**25.**	**31.3**	**0.702**	**0.685**	**1.082**	**0.595**	**0.874**
17 ♂	**162**	**248**	**24.6**	**31.**	**0.713**	**0.700**	**1.086**	**0.590**	**0.837**
18 ♂	**164**	**244**	**25.**	**31.2**	**0.703**	**0.690**	**1.074**	**0.608**	**0.795**
19 ♂	**158**	**247**	**26.**	**32.**	**0.729**	**0.710**	**1.145**	**0.607**	**0.803**
20 ♂	**162**	**253**	**28.3**	**31.8**	**0.752**	**0.718**	**1.152**	**0.600**	**0.857**
21 ♂	**156**	**239**	**24.6**	**30.5**	**0.659[1]**	**0.658[2]**	**1.042[3]**	**0.570[3]**	**0.810**
22 ♂	**166**	**251**	**27.5**	**31.5**	**0.720**	**0.691**	**1.118**	**0.612**	**0.847**
23 ♂	**165[3]**	**253**	**31. [1]**	**32.4**	**0.765**	**0.750**	**1.183**	**0.613**	**0.905**
24 ♂	**166[2]**	**250**	**28.3**	**32.4**	**0.754**	**0.718**	**1.179**	**0.607**	**0.916[3]**
Average	**162**	**247**	**26.2**	**31.6**	**.727**	**.706**	**1.120**	**.603**	**.845**

Table II.

Measurements of Sixteen Young Males which Survived

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
36 Juv. ♂	156	246	24.6	32.	0.741	0.735	1.167	0.592	0.849
37 Juv. ♂	156	245	25.5	32.1	0.761	0.717	1.147	0.620	0.816
38 Juv. ♂	163	248	24.8	32.2	0.742	0.733	1.165	0.606	0.854
39 Juv. ♂	163	248	26.3	33.	0.736	0.704	1.148	0.609	0.839
40 Juv. ♂	160	250	24.4	31.5	0.746	0.715	1.173	0.604	0.893
41 Juv. ♂	156	237	23.3	30.6	0.692	0.664	1.011	0.588	0.774
42 Juv. ♂	162	253	26.7	32.	0.759	0.734	1.197	0.630	0.878
43 Juv. ♂	163	2543	26.4	32.	0.766	0.750	1.165	0.605	0.886
44 Juv. ♂	164	251	26.9	32.	0.755	0.742	1.171	0.620	0.886
45 Juv. ♂	163	244	24.3	31.3	0.718	0.680	1.082	0.610	0.892
46 Juv. ♂	160	247	27.	31.5	0.764	0.732	1.177	0.617	0.846
47 Juv. ♂	160	250	26.8	32.5	0.764	0.729	1.123	0.6353	0.842
48 Juv. ♂	158	247	24.9	32.4	0.745	0.724	1.139	0.588	0.865
49 Juv. ♂	158	249	26.1	32.2	0.742	0.736	1.148	0.602	0.817
50 Juv. ♂	158	243	26.6	32.4	0.747	0.711	1.163	0.612	0.891
51 Juv. ♂	155	237	23.3	30.23	0.685	0.653	1.0111	0.587	0.794
Average	159	246	25.4	31.8	.741	.716	1.136	.607	.851

Table II[a]

Measurements of Twelve Young Males which Perished

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
25 Juv. ♂	**160**	**249**	**24.2**	**30.4**	**0.740**	**0.717**	**1.130**	**0.620**	**0.840**
26 Juv. ♂	**156**	**236**	**26.8**	**30.0**[2]	**0.690**	**0.671**	**1.067**	**0.563**[2]	**0.832**
27 Juv. ♂	**158**	**240**	**23.5**	**31.**	**0.715**	**0.702**	**1.113**	**0.595**	**0.805**
28 Juv. ♂	**166**	**245**	**26.9**	**31.7**	**0.715**	**0.695**	**1.107**	**0.604**	**0.847**
29 Juv. ♂	**165**	**255**[2]	**28.6**	**31.5**	**0.766**	**0.744**	**1.175**	**0.613**	**0.854**
30 Juv. ♂	**157**	**238**	**24.7**	**31.2**	**0.680**[3]	**0.677**	**1.156**	**0.599**	**0.769**
31 Juv. ♂	**164**	**250**	**27.3**	**31.8**	**0.764**	**0.726**	**1.171**	**0.588**	**0.860**
32 Juv. ♂	**166**[2]	**256**[1]	**25.7**	**31.7**	**0.752**	**0.751**	**1.187**	**0.595**	**0.858**
33 Juv. ♂	**167**[1]	**255**[2]	**29.**[3]	**32.2**	**0.765**	**0.745**	**1.197**	**0.638**	**0.855**
34 Juv. ♂	**161**	**246**	**25.**	**31.5**	**0.739**	**0.707**	**1.123**	**0.587**	**0.850**
35 Juv. ♂	**166**[2]	**254**[3]	**27.5**	**31.4**	**0.760**	**0.742**	**1.124**	**0.604**	**0.914**
36 Juv. ♂	**161**	**251**	**26.**	**31.5**	**0.731**	**0.707**	**1.122**	**0.589**	**0.828**
Average	**162**	**248**	**26.2**	**31.5**	**.734**	**.715**	**1.141**	**.599**	**.842**

Table III.

Measurements of Twenty-one Adult and Young Females which Survived

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
52 ♀	156	245	25.3	31.6	0.729	0.710	1.152	0.620	0.809
53 ♀	154[3]	240	22.6[1]	30.4	0.705	0.686	1.103	0.584	0.770
54 ♀	153[2]	240	25.1	31.	0.724	0.713	1.123	0.585	0.812
55 ♀	153[2]	236	23.2[3]	30.9	0.698	0.678	1.132	0.596	0.795
56 ♀	155	243	24.4	31.5	0.734	0.736	1.170	0.596	0.801
57 ♀	163	247	25.1	32.	0.748	0.734	1.166	0.602	0.821
58 ♀	157	238	24.6	30.9	0.726	0.727	1.175	0.588	0.797
59 ♀	155	239	24.	32.8	0.732	0.742	1.175	0.601	0.835
60 ♀	164	248	24.2	32.7	0.752	0.752	1.201	0.604	0.830
61 ♀	158	238	24.9	31.	0.741	0.689	1.091	0.592	0.866
62 ♀	158	240	24.1	31.3	0.733	0.706	1.107	0.591	0.867
63 ♀	160	244	24.	31.1	0.731	0.730	1.152	0.589	0.808
64 ♀	161	246	26.	32.3	0.758	0.732	1.154	0.623	0.859
65 ♀	157	245	24.9	32.	0.752	0.740	1.186	0.593	0.787
66 ♀	157	235	25.5	31.5	0.712	0.704	1.132	0.611	0.781
67 ♀	156	237	23.4	30.9	0.708	0.691	1.123	0.613	0.798
68 ♀	158	244	25.9	31.4	0.729	0.705	1.146	0.597	0.851
69 ♀	153[2]	238	24.2	30.5	0.715	0.707	1.116	0.595	0.821
70 ♀	155	236	24.2	30.3	0.727	0.705	1.120	0.585	0.790
71 ♀	163	246	27.4	32.5	0.732	0.711	1.163	0.630	0.862
72 ♀	159	236	24.	31.5	0.709	0.713	1.129	0.607	0.845
Average	158	241	24.6	31.4	.728	.714	1.143	.600	.819
General average for 72 birds	158	245	25.2	31.6	.736	.716	1.138	.603	.845

Table III^{a}.

Measurements of Twenty-eight Adult and Young Females which Perished

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
37 ♀	**155**	**240**	**26.3**	**31.4**	**0.709**	**0.710**	**1.123**	**0.614**	**0.815**
38 ♀	**156**	**240**	**25.8**	**31.5**	**0.715**	**0.678**	**1.127**	**0.597**	**0.812**
39 ♀	**160**	**242**	**26.**	**32.6**	**0.740**	**0.732**	**1.157**	**0.597**	**0.854**
40 ♀	**152**[1]	**232**[3]	**23.2**[3]	**30.3**	**0.676**[2]	**0.683**	**1.048**	**0.590**	**0.780**
41 ♀	**160**	**250**	**26.5**	**31.7**	**0.741**	**0.731**	**1.187**	**0.615**	**0.886**
42 ♀	**155**	**237**	**24.2**	**31.**	**0.727**	**0.723**	**1.118**	**0.610**	**0.787**
43 ♀	**157**	**245**	**26.9**	**32.2**	**0.766**	**0.751**	**1.227**[2]	**0.620**	**0.841**
44 ♀	**165**[3]	**245**	**27.7**	**33.1**[2]	**0.780**[1]	**0.757**[3]	**1.195**	**0.633**	**0.865**
45 ♀	**153**[2]	**231**[2]	**23.9**	**30.1**	**0.680**	**0.662**[3]	**1.042**[3]	**0.592**	**0.781**
46 ♀	**162**	**239**	**26.1**	**30.3**	**0.709**	**0.685**	**1.092**	**0.587**	**0.911**
47 ♀	**162**	**243**	**24.6**	**31.6**	**0.741**	**0.729**	**1.162**	**0.605**	**0.840**
48 ♀	**159**	**245**	**23.6**	**31.8**	**0.727**	**0.700**	**1.129**	**0.610**	**0.855**
49 ♀	**159**	**247**	**26.**	**30.9**	**0.711**	**0.666**	**1.098**	**0.580**	**0.749**[2]
50 ♀	**155**	**243**	**25.**	**30.9**	**0.730**	**0.711**	**1.127**	**0.598**	**0.839**
51 ♀	**162**	**252**	**24.8**	**31.9**	**0.752**	**0.738**	**1.180**	**0.615**	**0.875**
52 ♀	**152**[1]	**230**[1]	**22.8**[2]	**30.4**	**0.682**	**0.664**	**1.042**[3]	**0.551**[1]	**0.734**[1]
53 ♀	**159**	**242**	**24.8**	**30.8**	**0.717**	**0.667**	**1.090**	**0.575**	**0.809**
54 ♀	**155**	**238**	**24.6**	**31.2**	**0.706**	**0.702**	**1.102**	**0.588**	**0.758**[3]
55 ♀	**163**	**249**	**30.5**[2]	**33.4**[1]	**0.767**	**0.767**[1]	**1.207**[3]	**0.640**	**0.896**
56 ♀	**163**	**242**	**24.8**	**31.**	**0.713**	**0.713**	**1.128**	**0.607**	**0.813**
57 ♀	**156**	**237**	**23.9**	**31.7**	**0.718**	**0.716**	**1.090**	**0.611**	**0.800**
58 ♀	**159**	**238**	**24.7**	**31.5**	**0.726**	**0.701**	**1.145**	**0.600**	**0.800**
59 ♀	**161**	**245**	**26.9**	**32.1**	**0.751**	**0.704**	**1.142**	**0.607**	**0.819**
60 ♀	**155**	**235**	**22.6**	**30.7**	**0.695**	**0.692**	**1.119**	**0.584**	**0.771**
61 ♀	**162**	**247**	**26.1**	**31.9**	**0.751**	**0.735**	**1.157**	**0.618**	**0.802**
62 ♀	**153**[2]	**237**	**24.8**	**30.6**	**0.732**	**0.718**	**1.172**	**0.594**	**0.802**
63 ♀	**162**	**245**	**26.2**	**32.5**	**0.728**	**0.731**	**1.102**	**0.614**	**0.832**
64 ♀	**164**	**248**	**26.1**	**32.3**	**0.739**	**0.707**	**1.159**	**0.592**	**0.823**
Average	**158**	**241**	**25.3**	**31.4**	**.726**	**.709**	**1.1.31**	**.601**	**.820**
General average for 64 birds	**160**	**245**	**25.8**	**31.5**	**.728**	**.709**	**1.128**	**.601**	**.834**

Table IV.

The Maximum and Minimum Measurements

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
Maximum	**167**	**256**	**31**	**33.4**	(d)	**.767**	1.230	**.640**	.927
Minimum	(a) **152**	**230**	(b)	(c) 29.8	**.659**	.653	(c) 1.011	**.551**	**.734**

(a) The minimum length (152 mm.) occurs twice among the birds which perished: Nos. 40 and 52.

(b) The minimum weight (22.6 grams) occurs in each group: Nos. 53 and 60, and therefore is not entered.

(c) The minimum length of head (29.8 mm.) and of tibio-tarsus (1.011 inch) occurs twice among the surviving birds: Nos. 9 and 14, 41 and 51.

(d) The maximum length of humerus (.780 inch) occurs in each group: Nos. 6 and 44, and therefore is not entered.

Table V.

Average Departures from Ideal Mean

	Total Length	Alar Extent	Weight	Length of beak and Head	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Skull	Length of Keel of Sternum
Seventy-two which survived	2.51	4.20	10.9	2.51	16.	14.	29.4	10.	32.
Sixty-four which perished	**3.48**	**4.60**	**12.6**	**5.64**	**20.1**	**20.**	**33.8**	**12.**	**31.**

Appendix B: Bumpus’ Data

The data in this appendix are the same as those in Appendix A, but the formatting, lines, and superscripted notations have been removed. This format is more appropriate for saving as text and importing into a spreadsheet or statistical package (see Appendix C).

Table I.

Measurements of Thirty-five Males which Survived

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
1	154	241	24.5	31.2	0.687	0.668	1.022	0.587	0.830
2	160	252	26.9	30.8	0.736	0.709	1.180	0.602	0.841
3	155	243	26.9	30.6	0.733	0.704	1.151	0.602	0.846
4	154	245	24.3	31.7	0.741	0.688	1.146	0.584	0.839
5	156	247	24.1	31.5	0.715	0.706	1.129	0.575	0.821
6	161	253	26.5	31.8	0.780	0.743	1.144	0.607	0.893
7	157	251	24.6	31.1	0.741	0.736	1.153	0.610	0.862
8	159	247	24.2	31.4	0.728	0.718	1.126	0.609	0.793
9	158	247	23.6	29.8	0.703	0.673	1.079	0.602	0.820
10	158	252	26.2	32.0	0.749	0.739	1.153	0.614	0.857
11	160	252	26.2	32.0	0.741	0.723	1.129	0.624	0.892
12	162	253	24.8	32.3	0.766	0.752	1.134	0.633	0.923
13	161	243	25.4	31.8	0.721	0.722	1.126	0.597	0.891
14	160	250	23.7	29.8	0.730	0.703	1.103	0.590	0.820
15	159	247	25.7	31.4	0.729	0.717	1.141	0.592	0.927
16	158	253	25.7	31.9	0.743	0.699	1.150	0.600	0.860
17	159	247	26.5	31.6	0.733	0.714	1.155	0.611	0.923
18	166	253	26.7	32.5	0.767	0.765	1.230	0.600	0.878
19	159	247	23.9	31.4	0.752	0.723	1.113	0.602	0.825
20	160	248	24.7	31.3	0.752	0.737	1.176	0.603	0.803
21	161	252	28.0	31.8	0.770	0.731	1.190	0.590	0.885
22	163	251	27.9	31.9	0.769	0.745	1.168	0.622	0.860
23	156	242	25.9	32.0	0.723	0.711	1.116	0.609	0.886
24	165	251	25.7	32.2	0.751	0.742	1.161	0.613	0.865
25	160	247	26.6	32.4	0.728	0.707	1.108	0.590	0.836
26	158	244	23.2	31.6	0.730	0.713	1.142	0.585	0.888
27	160	242	25.7	31.6	0.709	0.705	1.124	0.620	0.788
28	157	245	26.3	32.2	0.741	0.726	1.143	0.595	0.850
29	159	244	24.3	31.5	0.723	0.698	1.107	0.615	0.847
30	160	253	26.7	32.1	0.739	0.714	1.117	0.592	0.864
31	158	245	24.9	31.4	0.726	0.703	1.119	0.580	0.854
32	161	247	23.8	31.4	0.735	0.694	1.101	0.602	0.789
33	160	247	24.6	32.3	0.756	0.745	1.135	0.607	0.905
34	160	247	27.0	32.0	0.755	0.736	1.174	0.631	0.873
35	153	241	24.7	32.2	0.728	0.680	1.092	0.592	0.884

Table Ia.

Measurements of Twenty-four Adult Males which Perished

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
1	165	249	26.5	31.0	0.738	0.704	1.095	0.606	0.847
2	160	245	26.1	32.0	0.736	0.709	1.109	0.611	0.842
3	161	249	25.6	32.3	0.743	0.718	1.128	0.602	0.828
4	162	246	25.9	32.3	0.738	0.709	1.135	0.607	0.869
5	163	250	25.5	32.5	0.752	0.731	1.197	0.623	0.888
6	162	247	27.6	31.8	0.731	0.719	1.113	0.597	0.869
7	163	246	25.8	31.4	0.689	0.662	1.073	0.604	0.836
8	161	246	24.9	30.5	0.739	0.726	1.138	0.580	0.803
9	160	242	26.0	31.0	0.745	0.713	1.105	0.600	0.803
10	162	246	26.5	31.5	0.720	0.696	1.092	0.606	0.809
11	160	249	26.0	31.4	0.726	0.689	1.097	0.602	0.850
12	161	250	27.1	31.6	0.737	0.711	1.120	0.631	0.852
13	162	248	25.1	31.9	0.744	0.722	1.154	0.591	0.839
14	165	252	26.0	32.3	0.726	0.710	1.145	0.609	0.887
15	161	243	25.6	32.5	0.709	0.707	1.122	0.607	0.832
16	161	244	25.0	31.3	0.702	0.685	1.082	0.595	0.874
17	162	248	24.6	31.0	0.713	0.700	1.086	0.590	0.837
18	164	244	25.0	31.2	0.703	0.690	1.074	0.608	0.795
19	158	247	26.0	32.0	0.729	0.710	1.145	0.607	0.803
20	162	253	28.3	31.8	0.752	0.718	1.152	0.600	0.857
21	156	239	24.6	30.5	0.659	0.658	1.042	0.570	0.810
22	166	251	27.5	31.5	0.720	0.691	1.118	0.612	0.847
23	165	253	31.0	32.4	0.765	0.750	1.183	0.613	0.905
24	166	250	28.3	32.4	0.754	0.718	1.179	0.607	0.916

Table II.

Measurements of Sixteen Young Males which Survived

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
36	156	246	24.6	32.0	0.741	0.735	1.167	0.592	0.849
37	156	245	25.5	32.1	0.761	0.717	1.147	0.620	0.816
38	163	248	24.8	32.2	0.742	0.733	1.165	0.606	0.854
39	163	248	26.3	33.0	0.736	0.704	1.148	0.609	0.839
40	160	250	24.4	31.5	0.746	0.715	1.173	0.604	0.893
41	156	237	23.3	30.6	0.692	0.664	1.011	0.588	0.774
42	162	253	26.7	32.0	0.759	0.734	1.197	0.630	0.878
43	163	254	26.4	32.0	0.766	0.750	1.165	0.605	0.886
44	164	251	26.9	32.0	0.755	0.742	1.171	0.620	0.886
45	163	244	24.3	31.3	0.718	0.680	1.082	0.610	0.892
46	160	247	27.0	31.5	0.764	0.732	1.177	0.617	0.846
47	160	250	26.8	32.5	0.764	0.729	1.123	0.635	0.842
48	158	247	24.9	32.4	0.745	0.724	1.139	0.588	0.865
49	158	249	26.1	32.2	0.742	0.736	1.148	0.602	0.817
50	158	243	26.6	32.4	0.747	0.711	1.163	0.612	0.891
51	155	237	23.3	30.2	0.685	0.653	1.011	0.587	0.794

Table IIa

Measurements of Twelve Young Males which Perished

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
25	160	249	24.2	30.4	0.740	0.717	1.130	0.620	0.840
26	156	236	26.8	30.0	0.690	0.671	1.067	0.563	0.832
27	158	240	23.5	31.0	0.715	0.702	1.113	0.595	0.805
28	166	245	26.9	31.7	0.715	0.695	1.107	0.604	0.847
29	165	255	28.6	31.5	0.766	0.744	1.175	0.613	0.854
30	157	238	24.7	31.2	0.680	0.677	1.156	0.599	0.769
31	164	250	27.3	31.8	0.764	0.726	1.171	0.588	0.860
32	166	256	25.7	31.7	0.752	0.751	1.187	0.595	0.858
33	167	255	29.0	32.2	0.765	0.745	1.197	0.638	0.855
34	161	246	25.0	31.5	0.739	0.707	1.123	0.587	0.850
35	166	254	27.5	31.4	0.760	0.742	1.124	0.604	0.914
36	161	251	26.0	31.5	0.731	0.707	1.122	0.589	0.828

Table III.

Measurements of Twenty-one Adult and Young Females which Survived

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
52	156	245	25.3	31.6	0.729	0.710	1.152	0.620	0.809
53	154	240	22.6	30.4	0.705	0.686	1.103	0.584	0.770
54	153	240	25.1	31.0	0.724	0.713	1.123	0.585	0.812
55	153	236	23.2	30.9	0.698	0.678	1.132	0.596	0.795
56	155	243	24.4	31.5	0.734	0.736	1.170	0.596	0.801
57	163	247	25.1	32.0	0.748	0.734	1.166	0.602	0.821
58	157	238	24.6	30.9	0.726	0.727	1.175	0.588	0.797
59	155	239	24.0	32.8	0.732	0.742	1.175	0.601	0.835
60	164	248	24.2	32.7	0.752	0.752	1.201	0.604	0.830
61	158	238	24.9	31.0	0.741	0.689	1.091	0.592	0.866
62	158	240	24.1	31.3	0.733	0.706	1.107	0.591	0.867
63	160	244	24.0	31.1	0.731	0.730	1.152	0.589	0.808
64	161	246	26.0	32.3	0.758	0.732	1.154	0.623	0.859
65	157	245	24.9	32.0	0.752	0.740	1.186	0.593	0.787
66	157	235	25.5	31.5	0.712	0.704	1.132	0.611	0.781
67	156	237	23.4	30.9	0.708	0.691	1.123	0.613	0.798
68	158	244	25.9	31.4	0.729	0.705	1.146	0.597	0.851
69	153	238	24.2	30.5	0.715	0.707	1.116	0.595	0.821
70	155	236	24.2	30.3	0.727	0.705	1.120	0.585	0.790
71	163	246	27.4	32.5	0.732	0.711	1.163	0.630	0.862
72	159	236	24.0	31.5	0.709	0.713	1.129	0.607	0.845

Table IIIa.

Measurements of Twenty-eight Adult and Young Females which Perished

Bird ID	Total Length	Alar Extent	Weight	Length of Skull	Length of Humerus	Length of Femur	Length of Tibio-Tarsus	Width of Width	Length of Keel of Sternum
37	155	240	26.3	31.4	0.709	0.710	1.123	0.614	0.815
38	156	240	25.8	31.5	0.715	0.678	1.127	0.597	0.812
39	160	242	26.0	32.6	0.740	0.732	1.157	0.597	0.854
40	152	232	23.2	30.3	0.676	0.683	1.048	0.590	0.780
41	160	250	26.5	31.7	0.741	0.731	1.187	0.615	0.886
42	155	237	24.2	31.0	0.727	0.723	1.118	0.610	0.787
43	157	245	26.9	32.2	0.766	0.751	1.227	0.620	0.841
44	165	245	27.7	33.1	0.780	0.757	1.195	0.633	0.865
45	153	231	23.9	30.1	0.680	0.662	1.042	0.592	0.781
46	162	239	26.1	30.3	0.709	0.685	1.092	0.587	0.911
47	162	243	24.6	31.6	0.741	0.729	1.162	0.605	0.840
48	159	245	23.6	31.8	0.727	0.700	1.129	0.610	0.855
49	159	247	26.0	30.9	0.711	0.666	1.098	0.580	0.749
50	155	243	25.0	30.9	0.730	0.711	1.127	0.598	0.839
51	162	252	24.8	31.9	0.752	0.738	1.180	0.615	0.875
52	152	230	22.8	30.4	0.682	0.664	1.042	0.551	0.734
53	159	242	24.8	30.8	0.717	0.667	1.090	0.575	0.809
54	155	238	24.6	31.2	0.706	0.702	1.102	0.588	0.758
55	163	249	30.5	33.4	0.767	0.767	1.207	0.640	0.896
56	163	242	24.8	31.0	0.713	0.713	1.128	0.607	0.813
57	156	237	23.9	31.7	0.718	0.716	1.090	0.611	0.800
58	159	238	24.7	31.5	0.726	0.701	1.145	0.600	0.800
59	161	245	26.9	32.1	0.751	0.704	1.142	0.607	0.819
60	155	235	22.6	30.7	0.695	0.692	1.119	0.584	0.771
61	162	247	26.1	31.9	0.751	0.735	1.157	0.618	0.802
62	153	237	24.8	30.6	0.732	0.718	1.172	0.594	0.802
63	162	245	26.2	32.5	0.728	0.731	1.102	0.614	0.832
64	164	248	26.1	32.3	0.739	0.707	1.159	0.592	0.823

Appendix C:
Instructor's Notes on Using Bumpus' Data

Bumpus' paper is a pedagogical gold mine, and not just because it is a classic in evolutionary biology. Close study of the paper can help students to better understand: the structure of scientific papers (especially the importance of clear documentation of methods); the value of statistics in summarizing quantities of data; the power of statistical inference; the importance of critically evaluating statistics; and finally, the necessity to continually and critically reexamine the literature. I strongly urge instructors to use it in their classes.

In terms of this chapter's material, Bumpus' presentation of the data in six tables was not designed for input to statistical packages. This provides a good opportunity for students to think about data entry, organization, verification, and analysis. The next section of this appendix discusses some of the issues involved. Later, I will discuss other valuable lessons students can take away from Bumpus' paper.

Data Organization and Entry

Although instructors might give students copies of Appendix B, or one of the prepared data files (see the "DC&O - Read Me First" file), I suggest that if time allows, students work in teams to organize and enter the data manually. A team should decide what variables should be entered, in what order, what software should be used, who should enter what data, and how the data should be verified.

I found that many students have not experienced the pitfalls of entering and verifying a reasonable quantity of data.[5] They tend to proofread by eye, rather than reading to a colleague, or doing other checks (e.g., having the spreadsheet compute averages to check against Bumpus'), and have no idea how many errors can creep in. A number have admitted to me (after the fact) that missing errors and having them caught is a humbling, but valuable, experience.

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[5] Even professional researchers occasionally omit essential data verification. I know a researcher who received data from a colleague and combined those data with his own. He and his students used the combined dataset and added to it for years before a student asked me for help formatting the axis of a table. We saw that some observations had the variable Year coded "9999". This was a common way to designate missing data in older statistical packages--but not in the one he was using. All of his regressions and correlation analyses that included the variable Year were seriously flawed if not completely bogus.

What variables should be entered and in what format? Most students are thoughtful enough to realize they need to enter age, sex, and vital status. But, how should they code those variables? Do they also realize the value of a unique number for each bird to aid in finding and correcting errors? If they omit an ID number, they may realize its value when they have to find errors. When teams compare their approaches, they learn how many ways there are to look at one set of rather simple data.

What type of software should they use for data entry? Even a word processor will work if they are familiar with one and know to use tabs to format columns. The data can be saved as a text-only file and imported into spreadsheet, database, or statistical package. However, a word processor is not very efficient for data entry: it requires more typing than alternatives and cannot usually do helpful computations. Entry into a stat package also involves excessive data entry. I would suggest a spreadsheet because repetitive data from one of Bumpus' tables (i.e., with the same sex, age, and vital status) can be entered once and then "filled down" the columns. Students can then do simple averages to check their data against Bumpus'.

To reduce the tedium of data entry, I suggest that each student need enter only a part of the data. Each team can then merge their data into one worksheet and trade their sheet with another team. The two teams then check each other's work. The smart ones use the power of a spreadsheet to compare their tables with those of the other team and display discrepancies. The data from one team can be "pasted" into the other's spreadsheet. A third area of the spreadsheet can be formatted to subtract one data array from the other. Any non-zero values will indicate differences that need to be checked. This is a simple, rapid process if they have spreadsheet skills (and a worthwhile learning experience if they don't). You might consider awarding points based on errors found. You may even make a contest of this--which team can find the most errors in the least time (or verify correctness most quickly). After all of the data have been entered and corrected, a single, corrected data file can be distributed to the class.

There is another interesting issue here. Bumpus' averages don't always match the computer's because of differences in mathematical precision and rounding. It's interesting to watch students trying to reconcile the differences. Many tend to believe the printed paper is "right" and they are in error, when in fact there is no difference in the data and the averages computed by the computer have greater precision than the printed ones. This can be a valuable lesson: just because it's in print doesn't mean it's correct.

After the Data Entry

Once the data have been entered, you may want to have students move on to other projects, or may choose to have them follow up with the BioQUEST Biometrics module. Many students want to start working with the data once they have entered them.

Students need not have a lot of high-powered statistics under their belts. Bumpus certainly didn't; he used nothing more than means, frequency counts, and mean deviations. I have students with little experience do only Chi-square (e.g., do mortality rates of males and females differ) and independent-sample *t* tests (e.g., are mean skull widths wider or narrower in dead birds). Those tests, combined with appropriate histograms, and scatter plots will keep them busy for a reasonable time.

Those with more statistics can also test assumptions such as those of normality and homogeneity of variance. Some will want to test whether variances are indeed less in survivors than in dead. In fact, this was a part of the first re-analysis of Bumpus' data (Harris 1911). Advanced students can add multivariate analyses such as factor analysis and discriminant analysis, MANOVA, etc. References in the Bibliography will provide lots of ideas.

Students often do not notice that some variables are measured in inches and some in millimeters. Those who don't understand statistics may comment that skull length is much more variable than skull width and don't realize that it should be about 25 times greater simply because the units are millimeters rather than inches. Even students who have had a statistics course may need to be reminded to convert inches to metric. Here again, a spreadsheet is handy, as is a statistics package that permits easy recoding.

I have had good success having each student (or team if the class is large enough) pick and evaluate one variable (e.g., femur length). They read what Bumpus said about their variable, analyze the data with the statistical tools available, and reach some conclusion. They then write a paper or present a short talk detailing their analysis.

Other Lessons

Bumpus' data have a number of lessons for fledgling biologists and statisticians. Aside from providing an exercise in data entry and organization, Bumpus' paper makes an excellent case study that provides many lessons, and makes a wonderful contrast to modern papers. Here are some of the points students can take away from Bumpus.

Statistics compactly summarize volumes of data. One comment students make is how difficult it is to really grasp Bumpus' evidence. There are a lot of references to individual birds' measurements, counting of exponents in the six raw-data tables, and a table of maximum and minimum measurements where the key evidence is which numbers are in boldface text. Modern methodology could summarize Bumpus' six raw-data tables with a much more compact table with six rows of sample sizes, means, and standard deviations for the nine measurements. That's a largish table, 162 numbers, but a 45-fold decrease from the 7,344 Bumpus used!

A picture is worth a thousand words, but not all pictures are created equal. A truism, but more meaningful if students wrestle with a variety of graphs themselves. Six histograms and/or boxplots give a much better picture of the raw data than six tables of numbers. In fact, the six histograms could have the sample sizes, means, and standard deviations printed on them. Even more compactly, students could produce three paired boxplots (living and dead for the sex/age subgroups); this may also be more inferentially useful. Different teams often choose different representations of the data and you can ask them to debate which is the “best” summary of the data.

Inferential statistics provide guidelines for decisions about significance. Bumpus made a number of judgments about the significance of differences between averages of subgroups. If you ask students to find and discuss a number of those statements, they will often find it difficult to agree on how large a difference must be to be considered significant. They begin to appreciate the need for guidelines and the value of methods of statistical inference.

There is a need for those seemingly boring Methods and Materials sections. For example, Bumpus did not describe how he treated the sparrows or how long he kept the survivors before sacrificing them. This is especially important when students analyze specific variables, which brings us to the next point.

Statistical significance doesn’t always mean biological significance. For example, the clearest, statistically most significant difference between survivors and dead was weight: dead birds were heavier than live birds. When students realize that, an obvious next step is to ask *why* heavy birds were more likely to die. Students often understand the value of a high volume-to-surface ratio in cold climates and cite Bergmann’s Rule. They are at a loss to explain why Bumpus’ data seem to violate the rule. The better thinkers may realize that by definition, the survivors lived longer than the dead and must have continued to lose weight through respiration, urination, and defecation. Bumpus does not tell us whether he fed and watered the birds, or how long the survivors were allowed to live. In the end, students often realize that they can conclude nothing about the advantage or disadvantage of weight in surviving the snowstorm. The cautionary lesson that statistical significance does not always mean biological significance is but one of the many lessons to be learned from Bumpus’ paper.

History provides perspective. Following the historical sequence of papers that re-analyzed Bumpus' data provides an excellent series of snapshots of the development of statistics. Successive papers added measures of variance and confidence (Harris 1911), and eventually multivariate factor analysis (Johnston 1972) and attempts to measure the actual strength of selection (O'Donald 1973).