Research Methods Lecture 1:
Scientific Method and Critical Thinking

1.1 Scientific Methods

Most beginning science courses describe the scientific method. They mean something fairly specific, which is often outlined as

1. State a *hypothesis*; that is, a falsifiable statement about the world.
2. Design an experimental procedure to test the hypothesis, and construct any necessary apparatus or human organization.
3. Perform the experiments.
4. Analyze the data from the experiment to determine whether the hypothesis can be confirmed or disproved.
5. Refine or correct the hypothesis and continue if necessary.

This model of scientific investigation focuses upon starting with a hypothesis in order to prevent aimless wandering that occupies time and equipment without proving anything. It is particularly suited to medical research, where the hypothesis often concerns some new course of treatment that may be better or worse than conventional ones. However, there are many similar but different schemes that describe how certain research projects proceed. Here are some examples

1. Observe phenomenon
2. Identify *control variables* and *response functions*.
3. Design an experimental procedure to vary the response functions through the control variables keeping other factors constant.
4. Perform the experiments.
5. Analyze the relation between control variables and response, and characterize mathematically.

Much experimental physics proceeds along these lines. For example, if water is placed between two counter-rotating cylinders, there is a range of rotation speeds where the fluid develops a series of rolls. A research project might try to determine the boundary of the region of rotation speeds where these rolls occur, and the amplitude and wavelength of the rolls as a function of rotation speed, keeping the shapes of the cylinders fixed.

1. Identify a well-defined quantity.
2. Design a procedure to measure it with increased precision.

3. Perform the experiments.
4. Analyze the accuracy of the results.

This procedure seems conceptually simpler than many of the others, but it underlies much of the most expensive large group projects science. For example, one could describe the Human Genome Project in this way.

1. Learn the vocabulary and concepts of an existing area of mathematics.
2. Establish a relationship between two apparently different statements that can be expressed with this vocabulary.
3. Develop new vocabulary and proceed.

This model of research tries to capture what happens with pure mathematics. Sometimes the "relationship" takes the form of a conjecture that is easy to arrive at from many examples, and the hard part is proving it. At other times, the relationship could not possibly be imagined beforehand, and only emerges from the path that constitutes its proof. (In the case of Ramanujan, relationships that could not possibly be imagined without the proof are imagined anyway.) The origin of pure mathematics is particularly baffling since it seems to come out of nothing, and yet creates the most secure knowledge
we ever have in any branch of the sciences.

1. Identify a regularity or relation discovered through experimental investigation.
2. Build mental pictures to explain regularity, and develop hypothesis about origin of phenomenon.
3. Identify basic mathematical relations from which regularity might result.
4. Using analytical or numerical techniques, determine whether experimental regularities result from the starting mathematical equations.
5. If incorrect, find new mathematical starting point.
6. If correct, predict new regularities to be found in future experiments.

This mode of research describes much of applied mathematics, theoretical physics, theoretical chemistry, theoretical geology, theoretical astronomy, or theoretical biology. For example, the experimental observation might be intense bursts of _-rays. A hypothesis might be that they emerge from gravitational collapse of certain stars. A lengthy process of modeling the collapse of stars, trying to calculate the radiation that emerges from them, would be needed to check the hypothesis. In variants of this mode of research, the modeling takes place without any experimental input, and emerges with experimental predictions. In other variants, this type of research can lead to new results in pure mathematics.

1. Identify desired product or process.
2. Design procedure with potential to create desired outcome.
3. Build apparatus.
4. Determine whether proposed method produces desired result.
5. If not, modify until some approximation of desired outcome is achieved, until one gives up, or loses his job.
6. If so, optimize procedure with respect to speed, cost, environmental effects, and other market factors.
7. Bring product to market and continue.

Many large companies have one or more divisions devoted to "Research and Development." The research carried out in the corporate setting is usually more closely tied to an immediate profit-making goal than research in an academic setting. Here is a discussion of corporate research written by Ralph Bown, Director of Research at Bell Telephone Laboratories in 1950. Bell Labs was for around 40 years the greatest industrial laboratory in the world. The quotation is the preface to William Shockley's book *Electrons and Holes in Semiconductors*, which provided the scientific base for the creation of electronics:

"If there be any lingering doubts as to the wisdom of doing deeply fundamental research in an industrial laboratory, this book should dissipate them. Dr. Shockley's purpose has been to set down an account of the current understanding of semiconductors... But he has done more than this. He has furnished us with a documented object lesson. For in its scope and detail this work is obviously a product of the power an resourcefulness of the collaborative industrial group of talented physicists, chemists, metallurgists and engineers with whom he is associated. And it is an almost trite example of how research directed at basic understanding of materials and their behavior, "pure" research if you will, sooner or later brings to the view of inventive minds engaged therein opportunities for producing valuable practical devices....

In the course of three years of intensive effort [an] amplifier has been realized by the invention of the device named the transistor. It would be unfair to imply that any and every fundamental research program may be expected to yield commercially valuable results in so short a time as has this work in the telephone laboratories. "

To achieve such results, careful choice of a ripe and promising field is prudent and a clear recognition of objectives certainly helps; but there should be no illusions about the necessity of a large measure of good luck.

1. Create instrument or method for making observation that has not been made before.

2. Carry out observations, recording as much detail as possible, searching for anything unexpected objects or relationships.
3. Deliver results to other modes of research as appropriate.

This mode of research takes place whenever a new tool is developed, and covers an enormous range of possibilities. It describes the expeditions that revealed the different continents to our European predecessors and mapped the globe. It describes the increasingly accurate maps of the night sky created by new generations of telescopes, or new particles discovered in particle accelerators. One point of the conventional idea of the scientific method is to prevent this mode of research from proliferating once the techniques employed and objects found are no longer new.

1. Pose question or hypothesis.
2. Search for answer in existing information sources.
3. Evaluate quality of results, decide on reliability, proceed to other forms of research or stop as a appropriate.

Because of the vast quantity of research that has already been performed, it is irresponsible to begin a project without attempting to determine whether the answer is already known. Searches are becoming easier and easier through the internet, although such searches do not cover everything. It is still difficult to access Soviet contributions from the 1950’s and 1960’s, although they may be very significant, particularly for mathematics and physics. The drawbacks of relying too heavily on literature searches are that they can lead to a sense of despair as one contemplates the mass of prior work one must understand before beginning something new, the process of studying old results can stifle new ideas, and correct and incorrect work can be difficult to separate.

Critical Thinking: Inductive and Deductive Reasoning

Critical thinking is at the heart of the scientific method. Specifically, behind the process of designing, executing and interpreting the experiment is an adherence to deductive and inductive reasoning. All of you incorporate inductive and deductive reasoning into the way you live your lives; for example, none of you will purposely drop a glass onto the ground because you buy into the law of gravity and the fact that the glass will break. It is also true that very few of you, after buying sour grapes at the store a couple of weeks in a row, will buy them a third time (unless you like sour grapes.) By the way, I have just described the use of deductive and inductive reasoning in the two examples above.

Time Out for "Is Logical Thinking What we Really Want?" or "Why Do So Many People Believe in Crystals?"

Few people think they are illogical. Few professions promote illogical thought. Yet different professions have different standards for logical arguments. The same is true within science and mathematics. Mathematicians have the tightest standard, and the rigor of argument falls off as one moves away from mathematics. The first question we must address is what different people mean by logical thought. The importance of this question is that one of the reasons to teach science and mathematics to every student in the country is to promote logical thinking. In the past, addition and multiplication were survival skills in their own right. Now that the price ten Big Macs with tax can be determined by pushing on a picture of a hamburger, learning logical thinking is probably the most important goal. Precisely what form this logical thinking is supposed to take, and how learning science and mathematics are supposed to produce it is a question often ignored.

A popular image of the logical thinker is Sherlock Holmes. Here is how this (purely fictional) detective works:

"The portly client puffed out his chest with an appearance of some little pride and pulled a dirty and wrinkled newspaper from the inside pocket of his greatcoat. As he glanced down the advertisement column, with his head thrust forward and the paper flattened out upon his knee, I took a good look at the man and endeavoured, after the fashion of my companion, to read the indications which might be presented by his dress or appearance. I did not gain very much, however, by my inspection. Our visitor bore every mark of being an average commonplace British tradesman, obese, pompous, and slow. He wore rather baggy gray shepherd's check trousers, a not over-clean black frock- coat, unbuttoned in the front, and a drab waistcoat with a heavy brassy Albert chain, and a square pierced bit of metal dangling down as an ornament. A frayed top-hat and a faded brown overcoat with a wrinkled velvet collar lay upon a chair beside him. Altogether, look as I would, there was nothing remarkable about the man save his blazing red head, and the expression of extreme chagrin and discontent upon his features.

Sherlock Holmes's quick eye took in my occupation, and he shook his head with a smile as he noticed my questioning glances. "Beyond the obvious facts that he has at some time done manual labour, that he takes snuff, that he is a Freemason. that he has been in China, and that he has done a considerable amount of writing lately, I can deduce nothing else." Mr. Jabez Wilson started up in his chair, with his forefinger upon the paper, but his eyes upon my companion. "How, in the name of good-fortune, did you know all that, Mr. Holmes?" he asked. "How did you know, for example, that I did manual labour? It's as true as gospel, for I began as a ship's carpenter." "Your hands, my dear sir. Your right hand is quite a size larger than your left. You have worked with it, and the muscles are more developed." "Well, the snuff, then, and the Freemasonry?" "I won't insult your intelligence by telling you how I read that, especially as, rather against the strict rules of your order, you use an arc-and-compass breastpin." "Ah, of course, I forgot that. But the writing?" "What else can be indicated by that right cuff so very shiny for five inches, and the left one with the smooth patch near the elbow where you rest it upon the desk?" "Well, but China?" "The fish that you have tattooed immediately above your right wrist could only have been done in China. I have made a small study of tattoo marks and have even contributed to the literature of the subject. That trick of staining the fishes' scales of a delicate pink is quite peculiar to China. When, in addition, I see a Chinese coin hanging from your watch-chain, the matter be- comes even more simple." Mr. Jabez Wilson laughed heavily. "Well, I never!" said he. "I thought at first that you had done something clever, but I see that there was nothing in it, after all." *[Arthur Conan Doyle, "The Red-Headed League" (1892)]*

There are many examples of thinking of this type in Feynman's stories about himself. They are probably embellished, and probably essentially true. See "He Fixes Radios By Thinking," for example, which casts Feynman as a functioning Sherlock Holmes by the age of twelve. The ability to select a pertinent fact out of masses of irrelevant ones and to focus upon its significance is the hard part of the Holmes skill, more than the deductions. Most people have mixed emotions about this sort of logical thinking. Logic is opposed to emotion. It is opposed to humanity. An excess of logic leads to an imbalanced personality. Sherlock Holmes has a talent that many people want someone to have, but are not sure they want for themselves:

Of Kurt G¨odel, a foremost logician of the century, his brother Rudolf wrote:

My brother had a very individual and fixed opinion about everything and could hardly be convinced otherwise. Unfortunately he believed all his life that he was always right not only in mathematics but also in medicine, so he was a very difficult patient for doctors. After severe bleeding from a duodenal ulcer ... for the rest of his life he kept to an extremely strict (over strict?) diet which caused him slowly to lose weight. Towards the end of his life G¨odel became convinced that he was being poisoned and, refusing to eat to avoid being poisoned, starved himself to death. *[J J O'Connor and E F Robertson]*

Now back to a discussion of deductive and inductive reasoning:

Deductive reasoning is the process of taking a generalization you accept to be true, and, of necessity, making a specific conclusion.

Generalization → Specifics

Example 1. The law of gravity (a generalization) says that if you drop an object, it will fall to the ground allows for the following bit of deductive reasoning termed a hypothetical argument.

If I drop a glass, it will fall to the ground.

Example 2. Another kind of deductive reasoning, termed a categorical syllogism, provides for the following deductive argument, again with a generalization leading to a specific:

All men are mortal (a generalization),
Socrates is a man,
Therefore, Socrates is mortal (a specific.)

Note that in both cases, a general statement necessarily leads to a specific conclusion. Note also, that a defining feature of deductive reasoning is the 100% certainty of the conclusion.

Inductive reasoning is the process of taking a series of specific statements, and from them, drawing a general conclusion.

Specifics → Generalization

Example.

I bought sour grapes at the store on Tuesday,
I bought sour grapes at the store yesterday,
Therefore, if I buy grapes today, they will be sour.

Note that a defining feature of inductive reasoning is that there is always some level of uncertainty in the argument. For example, you can't say for sure that last night the produce man didn't replace the sour grapes with ripened grapes.

Summarizing the distinctions between Deductive and Inductive Reasoning.

Deduction	Generalization → Specific	Certainty of conclusion
Induction	Specifics → generalization	Level of uncertainty in conclusion

Now one of the reasons that there is confusion about inductive and deductive reasoning is that the two concepts are inextricably mixed, and in fact, as we will see, scientists meander back and forth between the two forms of reasoning.

A few more thoughts on deduction and induction:

Note that you have only a couple of options in creating a generalization for use in deductive reasoning:

- You can create a series of absolute statements that cannot be proved, for example, axioms in analytical geometry, or the Gospel According to Matthew

or

- You can collect sufficient data in an inductive fashion, and after achieving sufficient confidence, you can state a law to be used for deductive reasoning.

For example, inductively we learn that:

Bob died, Mary died, Phil died.
It seems that everyone you have every known has died.

Armed with this information gathered inductively, you produce a law about people dying:

All men are mortal

and use it to make a deductive argument.

Now this all may be a little confusing—what is to guarantee that a deductive argument is 100% correct? What if the generalization used in deductive reasoning is not true? Remember, just because someone bullies you with a deductive argument, doesn't make the logic sound. As we will see, there are two necessary conditions for an argument to be sound, validity and truth.

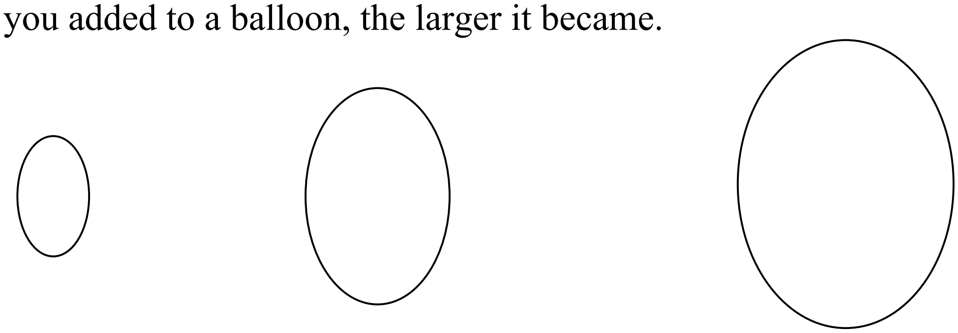
So how often are deductive arguments not sound? Actually it happens all the time. Recall that Newton gave us some very nice laws to describe the motion of objects, like

$$E = 1/2\ mv^2$$

and it worked for five centuries without exception, whether applied to planets or hopping kangaroos. However when the world of fundamental particles was discovered and investigated in the early 20th century, it was found that Newton’s laws no longer applied, and along came the theory of relativity to supplement Newton's work.

Now this doesn’t mean that Newton’s Laws are no longer used--they still are the foundational material for first year physics courses, but care has to be taken in defining the physical system to which they are applied.

Balloons and the Ideal Gas Law. Let’s look at an example of the interplay between inductive and deductive reasoning as applied to an example with which you have some experience, the filling of balloons with air. Of interest to scientists in the 17th century was the development of a set of rules explaining the process. The variables of interest were volume, pressure, temperature and the amount of air. In a first set of experiments, by none other than Avagadro, it was determined that the more air you added to a balloon, the larger it became.



small n medium n large n

This inductive process was repeated sufficient times to convince scientists that a proportional relationship could be developed that algebraically described the process.

$$V = k\ n$$

Where v is the balloon volume, n was the amount of gas in the balloon and k is the constant establishing the equality.

The ability to create a mathematical expression is the basis for later using **deductive reasoning** in efforts to describe what happens to the volume of a balloon filled with air.

In similar experiments, inductive reasoning was used to develop an understand the relationship between:

- Pressure and temperature
- Volume and temperature
- Pressure and volume

For each of these relationships, sufficient data was acquired to allow a series of algebraic expressions to be developed to describe the behavior of gases. This process of using **inductive reasoning** to gather data to support a law used for **deductive reasoning** gave us the ideal gas law

$$PV = nRT$$

where P is the pressure, T is the temperature and R is the ideal gas law constant.

Science did not stop here. Worked continued using the ideal gas law, with empirical data being acquired with increasing accuracy. The result was that scientists found that

$$PV \neq nRT$$

In this case inductive reasoning was once again employed as scientists acquired data to better understand gas phenomena. Out of this, a new and improved theory was developed that attempted to account for the non-ideal nature of the data. As if often the case the new equations modeling the data were more complicated—specifically, higher order terms were added to the ideal gas law. One example of a non-ideal gas law equation is the Vander Waal's Equation:

$$PV = nRT(1 + a/V \;+\; b/V^2)$$

The second and thirds order term accounted for the attractive forces between molecules and for the non-zero volume of the gas, two factors not considered in the original theoretical treatment.

This interplay between inductive and deductive reasoning is at the heart of how scientific research is conducted, with scientists engaged in a never-ending query for the truth.

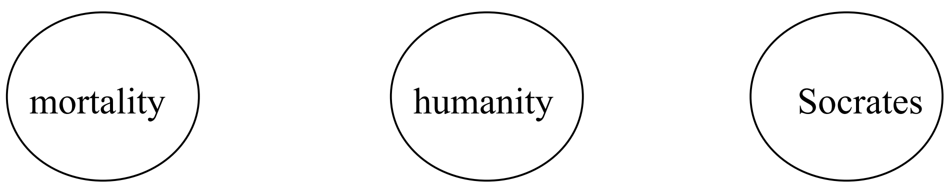
No wonder a famous turn-of-the-century mathematician and philosopher, Alfred George Whitehead, once wrote

"There is a tradition of opposition between adherents of induction and deduction. In my view it would be just as sensible for two ends of a worm to quarrel."

Creating a Logical Foundation for Deduction.

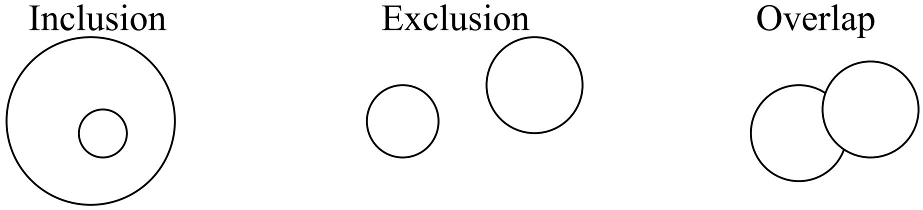
Feel free to take a logic course here at UT, but for now I give the most rudimentary of presentations to explain the logical foundation for deduction.

Class Logic. One form of logic, class logic, is based on the formation of classes that describe the specific properties of a group. For example, in the Socrates example, there are three classes

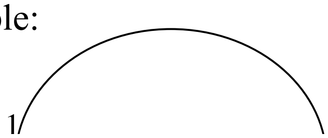


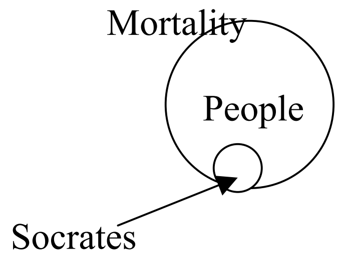
It is possible to develop a logical relationship between these three classes, recognizing that one of three things can happen between classes

Inclusion Exclusion Overlap



Whole courses on logic are developed to describe the relationship between classes in developing arguments. The most obvious (and only one) we look at here is called **categorical syllogism**. It is the simplest form of deductive argument and is constructed below for the Socrates example:





The reasoning goes that because the class of people are included in the class of mortality, and because Socrates is included in the class of people, then by necessity, Socrates in included in the class of mortality.

Are Deductive Arguments always true? Truth, validity and soundness.

At this point I have shown you only examples of sound reasoning. It is important, though, to understand the ways in which an argument can be illogical.

There are two requirements to accept a deductive argument:

- The structure of an argument must be **valid**
- The premises must be **true** (to the best of one's knowledge)

An argument that is both **valid** and **true**, is known as a **sound** argument. Let's distinguish between validity and truth to see where an argument can go wrong. First consider the following categorical syllogism:

All dogs bite
Fred is a dog
Therefore, Fred bites

This is an **unsound** argument because the first premise is **not true**.

Now consider a second argument:

All athletes are people
All football players are people
Therefore all football players are athletes

In this case, while each premise is **true**, the structure of the argument is **invalid** and hence, the logic is unsound.

One final example often referred to as "guilt by association" is another very common way that **unsound** arguments are made:

Doctors wear pagers
Drug dealers wear pagers
Doctors are drug dealers

Again, the circle diagram indicates the unsoundness of the argument.

Hypothetical argument. Another kind of deductive reasoning is based upon the hypothetical argument, one in which rather than form classes, conditions are applied. Hypothetical arguments can be identified by the presence of **if…then** statements.

If Bob puts on the brakes, the car will stop.
Bob puts on the brakes, therefore the car will stop.

In another form,

If Bob puts on the brakes, the car will stop.
Bob did not put on the breaks, therefore the car did not stop.

This is the basis for the idea of **cause and effect,** which is a foundational principle in science that we will return to in detail later. After all, it is the way we ask the question about whether a factor can influence the outcome of an experiment. For example,

Oxygen is needed for a fire to burn.
Oxygen is not provided, therefore the fire will not burn.

While this is true, the statement

Oxygen is needed for a fire to burn.
Oxygen is provided, therefore the fire WILL burn is not true.

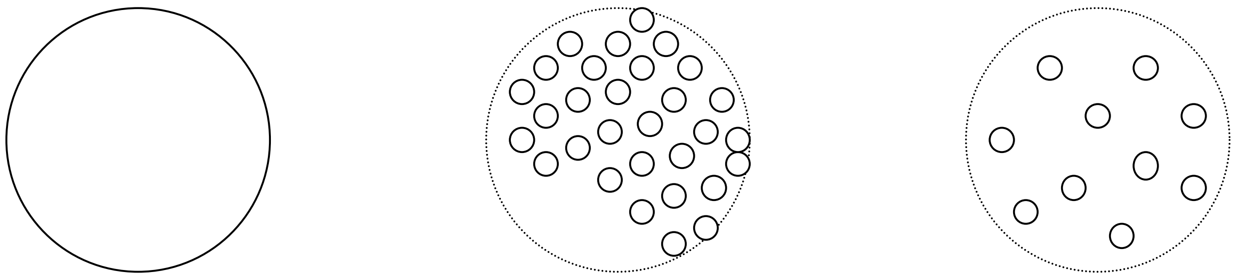
In deductive reasoning this is the distinction between **necessary** and **sufficient** arguments. In this case, the presence of oxygen is **NECESSARY** but it is **not SUFFICENT**.

A Foundation for Inductive Reasoning.

Only a brief discussion of **inductive** reasoning is provided here, because the topic will subjected to considerable scrutiny when a **statistical foundation** for induction is developed.

The fundamental distinction between deductive and inductive reasoning is that whereas a deductive argument can be accepted with **CERTAINTY** if **valid** arguments are used with **true** premises, an **inductive** argument is **NEVER CERTAIN**. Instead, inductive arguments can only be **statistical generalizations** with limited certainty. The mathematical foundation for inductive reasoning, then, rests with the development of procedures for effective sampling of a population to remove bias, and the creation of a level of statistical confidence in accepting the inductive reasoning.

The reason for the uncertainty and the reliance in statistics can be understood from the following data sets.



Case 1 Case 2 Case 3

Deductive reasoning sampling entire population
random sampling

Data set one is the circle formed in a deductive argument, which for example, states that all men are mortal. It is complete in itself. The second data set is a partial set formed by someone collecting data on every mortal creature in existence. Note that because not all the data has been collected, there is some uncertainty in the argument. This example, where all of the data is collected for a population, is tedious in the extreme. Far better would be the construction of a reasonable method for sampling the population. This is shown in the third example. In this case, **SAMPLING** is used to represent the true population. Again, there is uncertainty that must be measured, but at least a more time-efficient approach to collecting the data was used.

When **sampling**, what are some of the conditions that should be considered in creating an effective inductive argument?

- The size of the sample must be adequate
- The sampling must be random and representative

The explanation for the first statement is obvious, you aren't going to be very certain who will win the presidency by asking your neighbor Bob who he will vote for. You also aren't going to get a very good idea of the average height and weight of men at UT by hanging out in the athletic dorms on campus to create your sample.

The desired sampling conditions described above for good inductive reasoning are qualitative in nature. Is it possible to be more quantitative? Yes. In fact the field of sampling is at the heart of statistics and will be examined in here in detail in a later lecture. You will know the lecture when you see it--it is the dreaded lecture on statistics that you get in every good science course.

One final consideration is given to inductive reasoning: how much confidence is necessary for an inductive argument to be acceptable? The answer to this question varies from discipline to discipline, from experiment to experiment, from person to person. Although you will find certain fields in which confidence limits such as 95% or 99% are used (and conveniently tabulated in statistics tables), the answer really rests with the experimentalist and can vary significantly depending on how important the conclusion drawn is. For you as a teacher, how certain do you want to be in testing a student to determine whether he or she knows the material? Do you want to be able to be right 99% of the time, or only 80% of the time? Can you accept that one time in 100 times you will give a student a B who deserves and A, or can you live with getting it wrong 20 times in 100? This very personal decision is in fact what you, as a scientist, have to decide whenever you employ inductive reasoning.