TwoOldGuys™ Study Guides
BI114 Biological Concepts for Teachers
Chapter 1. Introduction
1.1. the Science Process

Based on Indiana's Academic Standards, Science, as adopted by the Indiana State Board of Education, Nov 2000.

Numbers refer to the age-appropriate grade-level for the content.

Many non-scientists consider that Science is somehow different from other disciplines, although few of them would be able to articulate how it is different. When asked, practicing scientists at universities will most often list a number of general characteristics which most scientific disciplines seem to share. On the other hand, authors of texts in the sciences tend to stress "the scientific method" as that which most distinguishes science from other disciplines. Too many teachers, at elementary and secondary level, think it is merely a matter of content that distinguishes science from the other subject areas. This section will describe what science is so the readers can draw their own conclusions as to how it differs from other disciplines.

General Characteristics of Science

When we sit down to write our textbooks (as many university professors expect to do sometime), we tend to think about what characteristics define science so we can explain to the introductory student how to do science. That we seek to define science so we can explain it is one important characteristic of science – we seek to define narrowly our terms and assumptions to assure that both the writer and the reader are in agreement concerning how the terminology is expected

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to be used and concerning what constraints (defined by the assumptions) apply to the discussion. We then allow an argument to be presented only to the extent that the arguments and conclusions (Theories) advanced are consistent with the assumptions. Yet, no matter how fond we are of any given theory, we remain prepared to reconsider it, and even abandon it, in the face of new facts or new theories. However, any theory offered must be testable, because the ultimate test of the validity of any new science idea is its verification through repeatable experimental proof. Although most introductory students wish it were not so, no matter how brilliant anyone's ideas may be, those ideas are of no value unless they are communicated in logically and grammatically correct style. This discussion suggests, then, that science is merely a means by which we can acquire new knowledge with some assurance that the new knowledge is valid.

Define terms and assumptions

In *Through the Looking Glass*, Lewis Carroll introduces us to a character who states, "'When *I* use a word,' Humpty Dumpty said in rather a scornful tone, 'it means just what I choose it to mean – neither more nor less'" (Carroll, 1970. p 164). This would seem to lead to a form of linguistic anarchy; however, this also provides a means by which we can assure that all participants in the discussion are in agreement as to the meaning attached to each key word. The writer or speaker retains the opportunity to use words to mean just what he chooses for them to mean, but he is obligated to publish his chosen meaning to the reader or listener. The more precisely the writer chooses to define his terms (and to publish his definitions), the more accurately the reader can understand the intended meaning of the information stream provided.

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Examples of definitions:

Tomorrow = "when next we meet as a class."

This definition is offered somewhat facetiously, to illustrate that scientists often use commonly understood words to mean something rather different than most people would expect them to mean. I have a habit of speaking of what my class will do 'tomorrow' even when a break (such as a holiday) occurs between today and the next class meeting, so I merely redefined 'tomorrow' to match my usage.

Interesting = "any idea or concept which we wish to discuss at any given moment."

To be a bit less facetious, most scientists appear to assume that if they are interested in Something, this means that The Something is inherently interesting. Students rarely agree with this definition when the teacher is applying it in the classroom, although the students frequently apply it to their own classroom behavior.

Usual approach = "the way I prefer to do it."

The first fundamental assumption with which we all begin our lives is that 'whatever we experience is universal!' (see below in the sub-section entitled "Logical Argument").

Fact = anything observable, either directly or indirectly.

To be 'observable' does not require being 'observed.' We can accept as fact anything observed personally or by any other person whom we consider to be a reliable observer. We can even accept as fact anything that we know *could* be observed when [not if] somebody determines how

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to observe it. Directly observable refers to the senses, while indirectly refers to any extension of the senses. For example, we can view distant objects through a telescope, or small objects with a microscope. We can also take photographs in 'colors' that the human eye cannot see (such as ultra-violet or infra-red); we have even photographed the sky in x-rays (extreme ultraviolet), and the surface of Venus in microwaves (radar or extreme infrared).

Anything which cannot be observed is not a fact, but an assumption or an explanation. For example, 'sunset' is an explanation of a collection of facts: at some time the sun was visible above the horizon; later the sun was partially obscured by the horizon; and still later the sun was fully obscured by the horizon. "The setting of the Sun" is one possible explanation to describe the facts; but it requires the Earth to remain fixed while the Sun travels around it. This is not our current model of the Solar System. It should be noted for those who may not yet have noticed, when we accept as fact something which could be observed as soon as somebody figures out how to observe it, we have assumed it to be true. You should also notice that 'facts' are boring by definition.

Hypothesis = a tentative explanation of a collection of facts.

Any time a scientist has come up with what he considers to be a reasonably good explanation of some data [defined, below, as a collection of facts], and has identified a means of testing [by experimentation] the validity of the explanation, he will express the explanation as a hypothesis. Only after having tested it, will he present it to his colleagues for their acceptance. A untested "hypothesis" can be presented to peers for review as an idea.

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Theory = a generally accepted hypothesis.

When a scientist persuades a group of her peers that her hypothesis is a good explanation of the data, the hypothesis can be considered to be a theory. Often, theories are expected to explain a larger domain of data than most hypotheses explain. Another name for 'theory' frequently encountered among scientists is 'model.' Strictly defined, theories and models require predictions of observable events which can be used to confirm (test) the theory.

Qualitative = descriptive fact, not able to be measured.

These facts will involve classes, discreet numbers (counting), or even illustrations.

Quantitative = a measurable fact.

These facts involve characteristics (such as length, weight, volume, etc.) which can be measured. This implies that the numeric value assigned to the characteristic is continuous, or has a decimal component.

Data (singular datum) = a collection of facts.

There is a tendency to use the term ‘data’ as if it implied quantitative rather than qualitative facts, but this is not part of the definition. The singular, ‘datum,’ refers to one fact from the collection or data.

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Measurement = an estimate of the quantity of some characteristic.

Inherent in the process of measuring is the chance for error. The 'simple' act of measuring the length of something with a ruler provides two opportunities for error: first you must line up the end of the ruler with the edge of the object, then determine which mark on the ruler matches up with the opposite edge. You can confirm this with a simple exercise, suitable for grades 3 through graduate school. Select any object and measure and record its length, then set the object and the ruler down, pick them back up and repeat the measurement. Another similar example is to weigh something, remove it from the scale, then reweigh it. In almost every case the second measurement will not be the same as the first attempt. [Note that my offering an experimental confirmation (which you could repeat) of an explanation here is an example of scientific thinking.] We assume that the average of several estimates is a better estimate than the individual values. To clarify the nature of the reported measurement, we have the terms: precise, accurate, and bias.

Precise = how repeatable a measurement is.

Translated into English, this definition means we need some estimate of the amount by which repeated measurements differ from each other. The statistical estimate [measurement] of the precision of a data set is variance or standard deviation about the mean.

Accurate = how close to the 'actual' value a measurement is.

We do not, and can not, know what the actual value is. We can only estimate it, so we need some accepted method for evaluating the

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accuracy of our estimates. The generally accepted method for this evaluation is Statistics. The statistical estimate [measurement] of the actual value is the grand mean [defined as the mean of several replicated means]; and the statistical estimate [measurement] of the accuracy of a data set is variance or standard deviation about the grand mean. For properly designed instruments, the scale marks are drawn such that the user can estimate 1/5th of a scale unit as the limit of the theoretical accuracy of the instrument. The actual accuracy of any instrument depends on who is operating it.

Bias = tendency of data to be consistently inaccurate.

We expect data to deviate from actual values randomly, and have included this expectation into the assumptions of statistics. Sometimes data will deviate from the actual values in some consistent fashion (such as always estimating speed to be more that it "really" is, which most automobile speedometers do), regardless of the level of precision. Similarly, if we repeat the exercise above (definition of measurement) with a fluid and a measuring cup, it is likely that each time the fluid is poured from one container to another, a small portion will be lost, producing progressively smaller estimates. Such data are said to be 'biased.' Normally, to detect bias, we must compare different instruments, or different observers.

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Examples of assumptions:

A major activity in science is to develop explanations for interesting data. The "usual approach" [see definition above] is first to identify patterns within the data. This should lead to determining the assumptions needed to develop the explanation. The next step is to use logical reasoning to proceed from the assumptions to the tentative explanation, which is referred to as the hypothesis. It is not unusual for the logical development of the hypothesis to reveal the need for more assumptions.

In the final communication of the hypothesis to the scientific community, it is essential to state explicitly *all* of the assumptions used in developing the hypothesis. Both in the logical development of the hypothesis and in the logical arguments in support of the hypothesis, the 'rules' of inductive reasoning demand that the argument must remain consistent with the assumptions. Clearly, the reader must have access to full disclosure of the assumptions in order to evaluate whether or not the argument is logically consistent.

Statistics, assumptions:

A fundamental premise (assumption) of statistics is

- The average [mean] of several estimates is 'better' than any one estimate, *and*
- variance (standard deviation) about mean estimates precision.

Statistical calculations on a single data set are said to be 'within estimates,' [symbolized **W/I**].

Deduction:

the Central Limit Theorem [a provable mathematical theorem] states that

- The average of several means, the grand mean, is more accurate than any one mean, *and*
- variance of the means about the Grand Mean estimates accuracy.

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Statistical calculations on several data sets to determine the grand mean and variance are said to be 'between estimates,' [symbolized **B/T**].

Data for statistical studies are generally symbolized as upper-case Y [or as a set, {Y}] if they are dependant variables, or as X [or {X}] if they are independent variables. In a cause – effect systems, the dependant variable is 'caused' by the independent variable; for example, it is often hypothesized that intelligent (estimated as IQ) 'causes' school success (estimated as GPA). Unfortunately, available data does not confirm this hypothesis.

The 'mean' is defined as the arithmetic average [symbolized as an overlined Y, pronounced "Y-bar"], calculated as the sum of the numbers divided by the number of observations:

$\text{Y-bar} = \Sigma Y/n$.

The 'deviate' [symbolized as a lower-case, italicized *y*] is defined as the difference between each observation and the mean of the observations:

$y = Y - \text{Y-bar}$.

The 'variance' [symbolized as sigma-squared (σ^2) or s-squared (s^2)] is defined as the sum of the deviates squared divided by the number of observations:

$\sigma^2 = \Sigma(Y - \text{Y-bar})^2/n$.

The 'standard deviation' is defined as the square root of the variance.

Example of assumptions in Biology:

In the *Species Concept and Phylogeny* (section 1.3 of this text), it is assumed

a) that evolution occurs, and
b) that evolution is linear, and
c) that evolution works on those traits which are easily observed,

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so a phylogenic tree based on systematics can describe evolutionary relationships.

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Logical argument

It is the ultimate goal of Science to explain how the universe works. This goal is, perhaps surprisingly, also the goal of your future students. All children are born with limited data on the new universe into which they have been thrust by the process of birth. As would any great scientist, they approach the attempt to understand how the universe functions with some assumptions. The first fundamental assumption of the new-born is that "whatever I experience is universal," or "all other children share similar experiences." For example, a particular child, born into a world (the delivery room) which is brighter, colder and harder than the world in which the child has spent the last nine months, will assume that all new-borns share this experience. Another child may be born into a pool of water rather than a delivery room, yet our first example of a child has no way of learning of this alternate universe within minutes of her birth. By the time the child enters into the educational system, he or she will have spent *years* collecting data, developing hypotheses to explain that data, and manipulating the universe in an attempt either to confirm his/her hypotheses or to gather additional data so new hypotheses can be developed. Thus your students were already practicing scientists before they met you.

Great, or even mediocre, scientists never out-grow the practice of continually gathering data about the universe, nor of continually revising their hypotheses to account for that universe. The first part, the gathering of data, seems at first glance to be straight-forward; one need only to observe carefully as one moves about the universe. However, a trained observer will come back with different data than will an untrained observer. Remembering the definition of bias, this suggests that either the trained or the untrained observer is biased. The best explanation of this bias is that the training process provides the observer with assumptions which are then used to bias the data; the trained

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observer is simply looking for data consistent with the assumptions, while the untrained observer does not know what he is looking for. This bias is usually considered to be reasonable (by the biased observers) since it is generally more comfortable to confirm one's hypotheses than it is to be forced to revise them.

If we are to maintain this comfort zone, then it would be desirable to develop a set of rules which, when followed, will maximize the likelihood that our hypotheses are good in the sense that they will be confirmed often. For this, we assume that the rules of logic provide the assurance that most of our hypotheses will be good. The expected sequence of events is as follows: we review the data in search of patterns; then use deductive reasoning to identify the minimum set of assumptions needed to explain the data; and finally derive the explanation from the assumptions by inductive reasoning.

For deductive reasoning, think of Sir Arthur Conan Doyle's Sherlock Holmes. For example, when first we, the readers of Strand Magazine in 1891, met the famous detective in “Adventure I. – a Scandal in Bohemia”, just after Dr. Watson has stopped to visit following an unspecified time without contact, Sherlock says to Watson,

> “Wedlock suits you,” he remarked. “I think, Watson, that you have put on seven and a half pounds since I saw you.”
> “Seven,” I answered.
> “Indeed, I should have thought a little more. Just a trifle more, I fancy, Watson. And in practice again, I observe. You did not tell me that you intended to go into harness.”
> “Then, how do you know?”
> “I see it, I deduce it. How do I know that you have been getting yourself very wet lately, and that you have a most clumsy and careless servant girl?”
> “My dear Holmes,” said I, “this is too much. ...It is true that I had a country walk on Thursday and came home in a dreadful mess; but, as I have changed my clothes, I can’t imagine how you deduce it. As to Mary Jane, she is incorrigible, and my wife has given her notice; but there again I fail to see how you work it out.”
> “It is simplicity itself,” said he; “my eyes tell me that on the inside of your left shoe, just where the firelight strikes it, the leather is scored

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> by six almost parallel cuts. Obviously they have been caused by someone who has very carelessly scraped round the edges of the sole in order to remove crusted mud from it. Hence, you see, my double deduction that you had been out in vile weather, and that you had a particularly malignant boot-slitting specimen of the London slavery. As to your practice, if a gentleman walks into my rooms smelling of iodoform, with a black mark of nitrate of silver upon his right fore-finger, and a bulge on the side of his top-hat to show where he has secreted his stethoscope, I must be dull indeed, if I do not pronounce him to be an active member of the medical profession." (Doyle, 1975. p 1-2)

For inductive reasoning, we could pursue a similar exercise. For example, **if (a)** the air temperature begins to drop as the sun sinks slowly in the west and continues to drop until sunrise, **and if (b)** the air temperature begins to rise at sunrise, **then (c)** [our hypothesis] the first frost of the season is most likely just before dawn (when the air temperature is still dropping), and **therefore** [our experimental proof] if we were to start the car a few minutes before sunrise, and run it until it warms up, then no frost would form on the windshield. [note: when I have tried this experiment (in Atlanta, GA), I have discovered the most likely time for early season frost to form is about 15 minutes *after* sunrise]. The difference in the conclusion and the hypothesis can be explained by noting that the assumptions, (a) and/or (b), are flawed. At sunrise, the rate at which the temperature is dropping slows, then reverses to a temperature rise with a slight time delay between sunrise and the lowest temperature of the previous night.

To communicate properly our hypotheses, we must state explicitly all of our assumptions. Unfortunately, the actual practice of science generally follows 'the' scientific method as a guideline for good practices rather than as a set of rules for the conduct of science.

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Willingness to abandon theories, given new facts or better theories

Recall that we use the rules of logic merely to maximize the probability that our hypotheses and theories are good in the sense that they will be confirmed often, not to assure that our hypotheses and theories are "correct." We understand that our theories are only the best available explanation given the known facts and the stated assumptions. Because we, and our colleagues, are continually seeking additional facts, the set of known facts tends to expand. Should any of the newly acquired facts fail to support the current explanation, we respond by reviewing the new facts to confirm their validity, and by reviewing the current explanation to determine if it needs to be revised or replaced. Similarly, should one of our colleagues offer a different explanation of the data, we respond by reviewing both the current and the newly proposed explanations to determine which is more logically sound, and which appears to explain the facts better. Whichever explanation seems superior will be adopted as the current explanation. If one of the possible explanations is more robust, it will be accepted as the current theory. In this context, robust means "able to explain a larger domain of data." The other event which will cause us to reconsider our explanations is for the assumptions to be challenged, or alternate assumptions proposed.

The point is that an extremely important aspect of Science is the expectation that our theories are tentative, and can be changed or replaced at any time. This rule applies to *all* current theories, including those in which we firmly believe, and even those which we personally have helped develop.

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Experimental verification of theories

The simplest description of the nature of experimental verification is that theories must provide a means of proving them false. The less simple explanation is that a essential feature of any theory or model is that it *must* predict some observable event which would occur if the theory were true, but would not occur if the theory were false. By the rules of Statistics, each time an experiment confirms the theory our confidence in the theory increases; but if even one experiment contradicts the theory then the theory cannot be true.

Communication of results

"If you were to develop a cure for the common cold, yet told no one about it, then the common cold will not be cured (me, in this text)." To put it another way, after all the intellectual effort required to come up with a brilliant new theory, it would be nice to get some recognition for your cleverness. Before packing your bags to dash off to receive (graciously of course) the Nobel Prize, you would first want to communicate your theory to your peers. This requires writing, preferably using the rules of grammar and composition in whatever language you decide to use. The resulting written document will be submitted for publication in a journal in the field, which adds the further requirement that you follow a style manual chosen by the editors of the journal.

a [not "The"] Science Method

A popular myth perpetuated by textbook authors is that The Scientific Method exists, and even that practicing scientists actually follow it. This is only a Myth. As explained above, Science is mostly a way of thinking about the acquisition of knowledge. The version of scientific method

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presented below is more of a recommended outline of a laboratory report than it is a method for doing science. Remembering that your students will have spent years *being* scientists before you ever meet them, your challenge is to encourage them to continue to be scientists without revealing your vast lack of scientific knowledge. [Hint: *my* challenge is to make you 'do' science in your classroom, without revealing *my* vast lack of scientific knowledge!]

1. Ask simple questions

There is a legend that Einstein was asked during an interview how he could come up with the answers to such difficult questions, to which he is supposed to have replied, “I don’t. I ask simpler questions.” Perhaps the ability to find simpler questions is the defining characteristic of ‘genius,’ but I prefer to believe that it is merely a skill developed through practice. When faced with what appears to be a difficult question, the first task is to find a simpler question.

One thing you do not have to worry about when teaching science to young children is finding questions; your students will provide you with an endless supply of questions. Many of their questions will be difficult. You do not want to attempt to answer difficult questions, so you must try to rephrase the question as one so simple that you can guess what the answer ought to be. A clue that a difficult question is going to follow is the single key word, “Why?” Two tricks are available to simplify why questions easily:

(1) replace the “why;’ for example, “*why* do crickets chirp?” becomes “*how* do crickets chirp?”

(2) answer the question with a question, such as “How could we find out?”

These are not the only ways to simplify questions, but are a start.

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2. guess answer

(we spell *guess* "hypothesis")

- a hypothesis should predict:

a) some observable event which will occur if conditions are met
b) but the event will not occur if conditions are not met.

One of the benefits of the simple question is that you can guess what the answer ought to be. The hard part is to decide how you will know that you are right. For example, I have read that grasshoppers chirp by rubbing their hind legs together. If that were true, then rubbing grasshopper legs together correctly would make the chirping sound.

3. conduct experiment to test hypothesis

- experimental group where conditions are met
- control group where conditions are not met

Since the predicted event is supposed to occur if conditions are met and not if conditions are not met, most experiments require a minimum of two attempts to draw a valid conclusion. In one version of the experiment, we must set up the conditions which ought to allow the predicted event to occur. For the second version of the experiment, we should set up the conditions so the predicted event ought not to occur. The first version is called the “experimental group,” while the second version is the “control group.” For the grasshopper chirping hypothesis, we need only break the legs off a dead grasshopper, and rub them together. Either they will or will not make a chirping sound.

4. draw conclusions

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- If event = T in experimental, AND event = F in control
  ~ shout "Eureka! I proved my hypothesis to be true."

or

- If event = F in experimental, OR event = T in control
  ~ shout "Eureka, I proved my hypothesis to be false."

In science, we always have successful experiments, because we will have proved something – either that our hypothesis was correct or that our hypothesis was incorrect.

5. write lab report

- Introduction
  - what are your question and your hypothesis?
  - provide any appropriate library research or other background information.
- Procedures (Materials and Methods)
  - like a recipe, in sufficient detail that anyone could repeat the experiment.
  - what supplies are needed (be specific), and how much of each.
  - what to do with the supplies.
- Data
  - what happened? qualitative and/or quantitative data; "just the facts, ma'm ..."
  - tables, graphs, pictures, etc.
- Conclusions
  - conclusion:
    - the hypothesis is true! *or*
    - the hypothesis is false.
  - [optional] how does this change our concept of how the Universe works?

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