Lecture One: The Scientific Method

WHAT IS SCIENCE? It is a method used by humans to try to make sense of the world (and universe) in which they live.

• APPLIED SCIENCE (a.k.a. "technology") - The seeking of information that is of immediate use/benefit.
• PURE SCIENCE - The seeking of knowledge for the sake of having knowledge.

Biology is the study of living organisms (from the Greek bios, meaning "life" and logos, meaning "discourse in or study of"). Within biology, there are several subdisciplines that are more narrow in focus. Here are just a few of the subdisciplines of biology...

- Microbiology - the microbiologist studies microorganisms, such as bacteria
- Genetics - the geneticist studies genes and inheritance
- Physiology - the physiologist studies metabolism and function of organisms
- Pathology - the pathologist studies mechanism and causes of disease
- Epidemiology - the epidemiologist studies how diseases spread through populations
- Embryology – the study of how organisms develop from zygote to maturity
- Histology - the histologist studies structure and function of organisms' tissues
- Entomology - the entomologist studies the biology of insects
- Ornithology - the ornithologist studies the biology of birds
- Herpetology - the herpetologist studies the biology of amphibians and reptiles
- Mammalogy - the mammalogist studies the biology of mammals
- Botany - the botanist studies the biology of plants
- Mycology - the mycologist studies the biology of fungi
- Ecology - the ecologist studies the functioning of ecosystems
- Evolutionary Biology – the study of how population and species change over time

Within each of these subdisciplines there are even more specific areas of study. Scientists all start their work by making OBSERVATIONS and noticing interesting things. That's what you all did when you went out and took pictures. But this is only the first step in a very proscribed procedure we call... THE SCIENTIFIC METHOD

"The process known as the Scientific Method outlines a series of steps for answering questions, but few scientists adhere rigidly to this prescription. Science is a less structured process than most people realize. Like other intellectual activities, the best science is a process of minds that are creative, intuitive, imaginative, and social. Perhaps science is distinguished by its conviction that natural phenomena, including the processes of life, have natural causes—and by its obsession with evidence. Scientists are generally skeptics."

(from Biology by Neil A. Campbell)

So don't confuse The Scientific Method with Science, in general. Also note that if something is outside the realm of scientific testability, the wise scientists will not presume that it is not true, nor that it does not exist. Some things simply are outside the realm of the scientific method.

Deductive and Inductive Reasoning

DEDUCTIVE REASONING: From the general case to the specific
(All birds have feathered wings. We know that sparrows have feathered wings. Therefore, we can deduce that "Sparrows are birds.")

INDUCTIVE REASONING: From a specific case to the general principle.
(Sparrows are birds. They have wings, and can fly. Robins, flamingos, owls, and eagles are birds, have wings and can fly. From this you might induce that "ALL BIRDS CAN FLY."
The problem with the latter is the "inductive leap": When you make the jump from many observations to saying that an observation is always true in all cases, you could be wrong.

Generalizations can be useful, but there may be EXCEPTIONS to a general rule, or that the "general rule" could even be wrong.

Let's take the example above. You suddenly come upon an ostrich. It has wings, and all the other characteristics you'd ascribe to a bird--BUT IT CANNOT FLY! Does this mean that your general rule is always wrong? No. But it does mean that there are exceptions, and you must be ready to find them. The human mind is creative in its inductive reasoning, but it is not infallible. This is why scientists also use deductive reasoning in science.

A common theme in scientific endeavors is the use of HYPOTHETICO-DEDUCTIVE REASONING: The formulation of an hypothesis (a tentative answer to a question) and the execution of experiments from which one may deduce a general answer to the hypothesis. The steps in this process include:

1. Observation
2. Asking a critical question
3. Developing hypotheses
4. Making predictions that can be tested
5. Performing experiments to test the predictions
6. Collecting and analyzing data
7. Making a logical conclusion based on experimental results

**EXAMPLE:**
1. **OBSERVATION:** Flamingos eat a variety of invertebrates that they strain from the silt. Interestingly, flamingo feather color is similar to that of the shrimps they eat.
2. **CRITICAL QUESTION:** Is the color of the flamingo related to the color of the shrimp in their diet?
3. **PERFORM A PILOT STUDY.** This is an experiment designed to tell you whether your observation is a real, repeatedly observable phenomenon, and not just a coincidence.
4. **DEVELOP A STATISTICAL HYPOTHESIS FOR YOUR PILOT STUDY:**
   a. Null Hypothesis: There will be no significant difference in feather color between a group of flamingos fed shrimp and another group fed a different diet.
   b. Alternate Hypothesis: There will be a significant difference in feather color between a group of flamingos fed shrimp and another group fed a different diet.
5. **MAKE A PREDICTION:** If flamingo diet is changed, its feather color will change.
6. **DESIGN AND CARRY OUT RIGOROUS EXPERIMENTS:**
   a. One group of flamingos gets a diet consisting of all items, including shrimp. *(Control – sometimes abbreviated as "con")*
   b. Other group of flamingos gets the same amount and type of food, but without shrimp. *(Treatment – sometimes abbreviated as "trt")*
      All other variables (habitat, light period, amount of food, etc.) are held CONSTANT in both groups.
7. **COLLECT AND ANALYZE DATA:**
   a. Possible result #1: No difference in color between trt and con groups.
   b. Possible result #2: Significant difference in color between trt and con groups.

The answer must be determined with a statistical test that tells you whether any difference between the groups is (2) due only to random chance or (2) not due to random chance.

If it's the latter, then the difference should be because of your variable, the shrimp in the diet).
8. CONCLUSION:
   a. If your statistics indicate result #1, then the null hypothesis cannot be rejected.
   b. If your statistics indicate result #2, the null hypothesis is rejected, and the alternative hypothesis is accepted.

But is that the end of the science?
• The results of your pilot study should suggest further experiments.
• For example, now that you know a diet of shrimp makes flamingo feathers pink, WHY is that?
• What is mechanism of shrimp \( \rightarrow \) flamingo intestine \( \rightarrow \) feather color?
• Now comes the more complicated (and perhaps most interesting) part of your study.

9. DEVISE COMPETING HYPOTHESES to explain why a diet of shrimp makes flamingo feathers pink. For example:
   a. shrimp pigment is transmitted directly from the bird’s intestines to the feathers.
   b. shrimp stimulate flamingos to make a pink pigment from other substances
   c. flamingos are so embarrassed to eat dainty shrimp that they constantly blush.
   d. fill in your clever explanation (hypothesis) here.

10. DESIGN AND CARRY OUT RIGOROUS EXPERIMENTS TO TEST EACH OF YOUR COMPETING HYPOTHESES.
    At the end of your study, you should be able to rule out all but one of your competing hypotheses. And THAT one should generate yet another set of competing hypotheses.

The scientific method is a little bit like climbing up a tree with bifurcating (i.e., branching in two directions) branches. At each branch point, you decide which branch to follow, and that should lead you to more branches and more choices.

HYPOTHESIS, THEORY AND LAW
Science is based on the attempt to explain the cause of indisputable observations (FACTS). It is not based on faith, hunches, belief, or hopes. At its best, science is a process of observing, predicting, and analyzing things we can absolutely see with our own eyes to be true.

THE HYPOTHESIS
• A scientific HYPOTHESIS is a TENTATIVE EXPLANATION of an observation.
• It can be a prediction is based on past experience about the phenomenon. It’s an "educated guess" about what you expect to be true about the observation.
• Multiple, competing hypotheses make good science. (If you have only one possible answer, you may bias your experiment and your analysis.)
• Hypotheses should be testable via experimental procedures or field studies based on the hypothetico-deductive approach.
• A hypotheses can be refuted (proven wrong, or FALSIFIED), but it CANNOT BE PROVEN TRUE. (It is impossible to perform enough experiments to be certain that the answer will always be the same, and that the same explanation will always hold true.)

Overall vs. Experimental Hypotheses
A researcher trying to explain an observation should try to consider as many possible explanations for that observation as possible. Choosing just one hypothesis can lead to personal bias!
• Each possible explanation is an OVERALL HYPOTHESIS.
• Two opposite EXPERIMENTAL HYPOTHESES (statistical hypotheses):
  - Null hypothesis (H\(_0\)) – stated in terms of no difference between two groups being compared
  - Alternative hypothesis (H\(_A\)) – opposite of the null hypothesis
THE THEORY
• A scientific THEORY is a well-substantiated explanation for some aspect of the natural world.
• It is an organized system of accepted knowledge that applies in a variety of circumstances to explain a specific set of observations.
• A theory is constantly subject to testing, modification, and refutation as new evidence and ideas emerge.
• One can use a theory to make predictions.
  Example: The Theory of Evolution by Means of Natural Selection: Species have changed over time because of differential reproduction. Those best suited to exploit their environment will leave more offspring (and more genes) to the next generation than those who are not as well suited.

THE LAW...
• A scientific LAW generalizes a series of observations that happens exactly the same way every time, as long as conditions are kept exactly the same.
• A scientific law can be used to predict the results of an action, but it does not explain why those results happened.
  Examples:
  First Law of Thermodynamics: Energy and matter can be neither created nor destroyed; they can only change in form.
  Second Law of Thermodynamics: Energy exhibits entropy: All organized energy must move away from its original source, becoming disorganized (chaos) as it moves away.

Presenting Your Research
Once you have done your experiment and analyzed your results and come to conclusions, it's time to share your work with scientific colleagues. This can be done at a scientific meeting (a symposium) by presenting a
- TALK (on stage, with a microphone and usually with PowerPoint) or a
- POSTER (a session in which people tour posters to read the posters and ask questions of presenters).

Eventually, you will publish your research in a scientific journal. A common format includes…

Abstract - a complete overview of the paper in a short paragraph
Introduction - in which you state the background and hypotheses of your research
Methods - in which you describe the procedures and materials you used in your experiment
Results - in which you present your calculations, tables, results, and statistical analysis of your data
Discussion/Conclusions - in which you explain to your readers why you saw the results you saw.
Literature Cited - in which you list all the literature you used and cited in your research paper.

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THE MYSTERY OF THE GLASS FROGS: A slide show and exercise.
We will now view a slide show about Glass Frogs (Centrolenella spp.) in Costa Rica, and try to develop some hypotheses about the evolutionary significance of the male's parental care