How Science Works

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2.1 Philosophical Principles in Science

All modern, natural sciences follow a deductive process. From observations of the world around us, hypotheses are phrased that allow for certain predictions. Hypotheses are tested using appropriate methods, and the results are interpreted on the basis of existing knowledge.

The critical rationalism[1] (e.g., Popper 1935) holds that science proceeds by falsifying existing hypotheses and that hypotheses cannot be verified. Science proceeds by rejecting hypotheses and replacing them by alternate, yet untested hypotheses (that present more plausible explanations in the light of the results of the study). If the results of a study do not reject the existing hypothesis, the hypothesis (H_0) persists, but one cannot be sure that it is correct—it just represents the currently best available explanation until it is rejected and replaced by a better one. Failure to reject a hypothesis must not be interpreted as verification of that particular hypothesis; it is possible that either the methods to test the hypothesis were inappropriate or the alternate hypotheses may have been incorrect.

Tests, i.e., experiments or comparisons, are designed in the context of existing knowledge and they provide empirical data which allow for explanations. Ideally, tests are experiments and provide proximate causal explanations. However, in biology tests may also be comparative or correlational. Indeed, among the natural sciences, biology is special because explanations in biology have an

[1]Of course, other philosophical concepts of the foundations of science exist and critical rationalism is not without critique. However, until today it still stands as the most widely accepted concept explaining how science works.

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ultimate (historical, evolutionary) and a proximate (mechanistic) component (Bock 2017). Ultimate, historical, evolutionary causations require comparative/correlational methods and a phylogenetic tool-set. Proximate causations can be tested by experiments. Because organisms are inevitably historical (descendent by evolution) and functional, biological research is always concerned with both, ultimate and proximate explanations.

2.2 Principles of Scientific Methodology

> What is absolutely essential in the scientific methodology is not that empirical observations are made, but that these observations are objective as opposed to subjective—hence the term objective science. Objective empirical observations in the philosophy of science means that the same observations can be made by any person having the abilities to do so (Bock 2007).

An implicit corollary of the philosophical concept of science is that it requires communication among scientists. Only when hypotheses, tests, and results are communicated are they open to further testing by independent researchers and thus scientific progress is possible. This characterizes a scientific methodology which became established as standard among researchers in natural sciences. Over the centuries, this methodology has been formalized in publications (among other forms) and principles of communicating science have been established. Some of these principles have been consolidated as laws (e.g., copyright) others are rather "industrial standards" of the community, i.e., generally accepted and practiced, but open to challenge and development.

The pillars of scientific methodology are *reproducibility*,[2] *transparency*, and *honesty*! *Reproducibility* means that each study must be documented so that anybody else can precisely replicate the exact study. *Transparency* refers to the complete and correct documentation of the used materials and methods, including access to materials. *Honesty* refers to the complete and detailed documentation

[2]**Reproducibility** refers to the variation in measurements made on a subject under changing conditions, i.e., different measurement methods or instruments being used, measurements being made by different observers, or measurements being made over a period of time. In contrast, **repeatability** refers to the variation in repeated measurements made on the same subject under identical conditions. This means that measurements are made by the same instrument or method, the same observer (or rater) if human input is required, and that the measurements are made over a short period of time.

of a study so that all necessary details are given that are needed to reproduce the study. Science is based on honesty because fraud at the lab-bench level is practically impossible to detect.—Maintaining the integrity of science requires the collaborative effort of all parties involved: researchers, institutions, funding agencies, legislation, and journals—and it requires additional tools for peer review.

2.3 The Ethical and Legal Framework of Science

Science per se has no moral and no law—however, for the welfare of humans and the world around us, science has to proceed within the legal and ethical framework defined by humans. This framework is usually represented by the national law of the country in which the research is conducted and science must proceed within the (national) framework of copyright, animal protection, ethical rules for animal experimentation, protection against discrimination, and protection of ethnical minorities. The disparity of nations results in an according diversity of legal regulations.—Some journals/editors therefore also request respect for international agreements (e.g., International Whaling Commission; Convention of International Trade in Endangered Species, CITES) to avoid the relaxed conditions of some nations.

2.4 Science in the Real World

Scientists are embedded in a societal and political environment and the governments of most industrial nations have set goals for science, research, and innovation. By providing goals, guidelines, and funding, governments actively direct how science is organized and how science is communicated. For example, the European Commission calls for *open science*, which entails the ongoing transitions in the way research is performed, researchers collaborate, knowledge is shared, and science is organized (Walsh 2016). By promoting '*sharing knowledge as early as possible*,' politics actively aim at pre-review publication thus modifying communication of science. By setting political goals also on how science is organized, politics engage actively in the development of science and the societal context of science (European Commission 2008; Pan and Kalinaki 2015).

It would be naïve and not reasonable to assume that science would be free. Scientists are responsible for following the principles of science and for proceeding within scientific methodology, but they are also embedded in an ethical, legal, social, and political environment that contributes to the validation and acceptance of science.—We need to understand the processes in the system, the different rules a person can take in the system, the responsibilities, and the limitations of the system to act responsibly as members of the community and to potentially contribute to its further advancement—or, as Csiszar (2016) stated: "*[…] Peer review did not develop simply out of scientists' need to trust one another's research. It was also a response to political demands for public accountability. […]*"

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