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SCIENTIFIC GOALS AND METHODS

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Title: **Scientific Goals And Methods**

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Output Skills (Knowledge):

K1. Define "science" and describe the three essential components of a science.

K2. State what precautions and methods are useful for avoiding ambiguity in the scientific processes of observation, description, and formulation of theories.

K3. State the criterion for validity of a scientific theory and contrast it with other possible criteria.

K4. State criteria for a good theory.

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SCIENTIFIC GOALS AND METHODS

Abstract:
Before starting our study of physics, it is useful to specify explicitly our goals so that we have a clear sense of direction and can proceed without confusion. Accordingly, we shall begin this first part of the book by examining some fundamental issues common to all the sciences. These issues are particularly relevant in physics since it is such a highly developed science with far-reaching implications which transcend our common-sense notions. Thus physics demands a more critical examination of questions which can be more readily glossed over in other fields.

Let us then use this unit to discuss these questions: What are the goals of any science? What is needed to achieve these goals? What is included within science and what is not?

SECT.

A SCIENTIFIC GOALS

Throughout our lives we use our sense organs to make innumerable observations which we try to organize in our minds so that we might know what to expect in various situations. To pursue this task more systematically, we would deliberately make many observations and would try to invent theoretical ideas useful for relating and predicting as many observations as possible. We call this systematic activity a "science," in accordance with this definition:

Def. **Science**: A systematic activity aimed at inventing a unified and simple theoretical structure for relating and predicting the largest range of observations. (A-1)

Let us look somewhat more closely at the basic components of this definition:

(1) *Observations*: Observations are sense impressions that can be described in the simplest possible terms. Thus they involve typically words such as "seeing," "hearing," or "smelling." (For example, an observation might be described by the statement "I saw a dark circular spot when looking through the microscope.")

(2) *Definitions describing observations*: To describe observations, one uses various symbols (such as words, letters, numbers, drawings, etc.). Accordingly, one must specify procedures defining how specific symbols are to be connected to particular observations.

(3) *Theoretical structure*: Starting with the symbols describing the original observations, one can often obtain more useful descriptions by introducing convenient new symbols related by defining rules to the previously introduced symbols. In addition, one can introduce special rules, called "principles," for relating various previously defined symbols (e.g., rules of grammar, rules of logic, rules of algebra, or scientific principles). This process of symbol manipulation can be elaborated by defining further new symbols in terms of old ones and deriving new principles from more basic ones (just as we use ordinary language to define new words and to construct new sentences). The final result is a theoretical structure (i.e., a set of symbols and rules) designed to be useful for relating and predicting a large range of observations. A "theory" accounting for a particular set

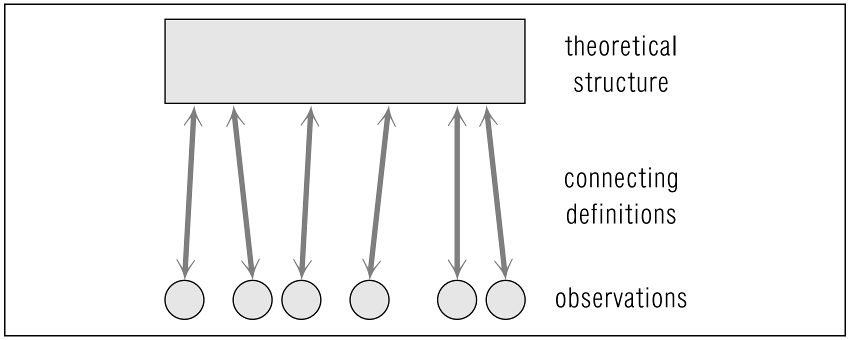

Fig. A-1: Schematic diagram illustrating the three essential components of a science.

of observations is thus a theoretical structure which successfully relates and predicts these observations.

The preceding three components of a science are indicated schematically in Fig. A-1.

Example A-1:

To illustrate how a theoretical structure can be used to predict some observations on the basis of other observations, let us consider a simple example from astronomy. One can make visual observations of the sun, the moon, and the planets during some one day of the present year. By using connecting definitions, one may then assign various symbols to these observations (e.g., symbols such as the words "position" and "velocity," and various numbers which can be associated with these words). The astronomer's theoretical framework now provides other useful symbols (such as the words "force" and "mass"), associated algebraic symbols (such as F and m), and some special rules for relating these symbols (rules expressed by equations called "law of motion" and "gravitational force law)." After manipulating these symbols according to the prescribed rules, one can then find what numbers are associated with the word "position" at any time in the year 2000. By using the connecting definitions to relate these symbols back to observations, one is thus able to predict that a darkening of the moon (i.e., an "eclipse") will be observed in Brisbane, Australia, at 11:55 PM on the 16th of July in the year 2000.

Although our definition of a science, Def. (A-1), may initially appear trivial, a serious pursuit of the goal specified in this definition has very far-reaching implications. In particular, it is apparent that the goal can

only be attained if one satisfies these requirements:

(1) One must be careful to be unambiguous (since no clear-cut predictions would otherwise be possible).

(2) One must accept any theoretical structure as valid only if it is successful in relating and predicting observations.

(3) One must have some methods for inventing successful theories.

We shall use the next three sections to discuss these important requirements and to contrast them with conditions common in everyday life or in non-scientific fields.

SECT.

B AVOIDANCE OF AMBIGUITY

IN SCIENTIFIC WORK

In doing scientific work, it is essential to avoid ambiguity at all stages. Otherwise it would be impossible to attain the goal of making definite predictions. (Indeed, if some things are unambiguously wrong, it is at least possible to eliminate them from consideration,or to diagnose and correct their specific deficiencies. But if things are ambiguous, it is impossible to draw any definite conclusions.)

Let us then consider what precautions and methods are useful for avoiding ambiguity in the scientific processes of observation, description, and formulation of theories:

(1) *Observations*

To avoid ambiguity in observations, one tries to refine the methods and conditions of observation so as to make the observations as reproducible as possible. [For example, the observation that water in a lake is "warm," as determined by the feeling experienced by a hand immersed in the water, is quite ambiguous since different observers (or even the same observer) may not agree on the results of several repeated observations. On the other hand, an observation method based on looking at a "thermometer" immersed in the water leads to much greater agreement and correspondingly to much less ambiguity.]

(2) *Definitions describing observations*

Any rule prescribing how to connect a descriptive symbol (such as a word or number) to an observation must specify unambiguous procedures for establishing this connection. Thus this rule of description must be an "operational definition," where the word "operational" indicates a specification of what one must actually do in order to connect a symbol with something else.

Def. **Operational definition**: An explicit specification of what one must do to connect a symbol with the thing it is designed to describe. (B-1)

Such an operational definition of a symbol describing an observation avoids ambiguity since it specifies explicitly what one must do to test

whether the symbol has been correctly assigned or not.

For example, the dictionary defines elapsed "time" in terms of "duration." This is merely a vague statement about a conventional association between words. It is not an operational definition of time since it does not specify what one must do to determine whether some elapsed time is longer than another, or what one must do to determine whether it is true that a particular elapsed time is 2 hours. On the other hand (as we shall see in the next unit), it is possible to give an operational definition of elapsed time by specifying how to use definite procedures with a clock in order to assign a meaning to the word "time."

(3) *Theoretical structure*

Any rule prescribing how any new symbol in the theoretical structure is to be connected to any previously defined symbol must again specify unambiguous procedures for establishing this connection, i.e., it must again be an operational definition specifying what one must do to establish the connection. (For example, the new symbol x^2 is operationally defined by the procedure of multiplying x by itself.)

Furthermore, it is essential that all the rules in the theoretical structure are unambiguously specified and that their application does not lead to contradictory results. Otherwise the theoretical structure would not be "self-consistent" and could not possibly be used to make unambiguous predictions.

Finally, it is important not to confuse theoretical statements with descriptions of observations, especially since the same observation might well be given different theoretical interpretations. [For example, the statement "I see something through the microscope" is a description of an observation, but the statement "there is something on the slide below the microscope" is a theoretical statement which predicts various observations which could be made to test the statement, e.g., which predicts that the thing will be observed to move if the slide is moved. (In fact, what one sees through a microscope may sometimes be merely a spec of dust on a lens.)]

CONTRAST WITH EVERYDAY LIFE

The language (i.e., the set of symbols and associated rules) which we use in everyday life is often fairly ambiguous. Indeed, as we grow up from early childhood, we begin to produce and recognize various sounds and visual symbols, gradually coming to associate them with specific observations or other symbols. Since this process of language acquisition is neither systematic nor critical, it leads to a language with much vagueness and ambiguity, although adequate for most needs of daily life.

The language used in science must satisfy much more stringent requirements: (1) All words and other symbols used in science must be operationally well defined to assure that they have unambiguous meanings; (2) All such words and other symbols must ultimately be related to observations since the only purpose for the use of scientific symbols is to relate and predict observations. (The relation between a symbol and observations need not be direct since such a symbol may be related by a series of operational definitions to other symbols, provided that the final symbols in this chain are related to observations.)

The previous comments can be summarized by this statement:

All symbols used in science must be operationally well defined so as to be ultimately related to observations	(B-2)

To satisfy this requirement, one must exercise much greater care in the use of scientific language than is usual in the language of daily life. Indeed, it is wise to consider any word of ordinary language as scientifically meaningless unless one can explicitly show that it is operationally well defined and is ultimately related to observations. Any word that does not meet this criterion merely adds confusion and should be discarded as scientifically irrelevant.

For the sake of convenience, one often uses in science many common words (such as "velocity," "force," "work," "energy," etc.) with precisely defined scientific meanings which may be quite different from the vague meanings commonly associated with these words in daily life. In these cases particular care is required to avoid confusion. Thus these words must be used according to their precise scientific definitions and should not be associated with any irrelevant connotations derived from daily life.

Attention to the unambiguous use of scientific language is not a pedantic concern, but a matter of great importance. For example, the two outstandingly successful physics theories of this century, the theory of relativity and the quantum theory, both arose out of the realization that certain words (such as "time" or "path of a moving particle") had been used with ambiguously specified meanings. The subsequent effort to eliminate such words,or to define them operationally, led to profound

changes in human thought and to new theories with far-reaching practical applications.

SECT.

C OBSERVATIONAL CRITERION OF VALIDITY

VALIDITY AS A CRITERION

According to the goal specified in the definition of a science, Def. (A-1), the purpose of a scientific theoretical structure is to relate and predict observations. Hence a scientific theory should be accepted (and thus called "valid") *only if* it is successful in relating and predicting observations.

The strict adherence to this observational criterion of validity is the basis for the successful development of modern science during the last four centuries. It is crucially important that this observational criterion of validity be clearly kept in mind in all scientific work. Thus one must be careful not to confuse this criterion with other criteria prevalent in everyday life or in other fields of human endeavor.

CONTRAST WITH OTHER CRITERIA

Self-consistency: The self-consistency of a scientific theory is necessary to assure that its predictions are unambiguous, but it is *not* sufficient to assure that the theory should be accepted as valid. Indeed, a theory might be beautifully self-consistent, but lack any validity because it does not correctly predict observations. [By contrast, pure mathematics is not concerned with observations (i.e., it is not a science), but is solely interested in discovering self-consistent relationships between various symbols. Thus a theoretical structure in pure mathematics is accepted as valid if it is self-consistent, without reference to any observations.]

Conformity with other considerations: The validity of a scientific theory does *not* depend on whether it agrees with any philosophical or other preconceptions. Thus a scientific theory need *not* conform with any philosophical ideas about the world; it need *not* include certain concepts or words such as "reality," "existence," or "truth"; it need *not* agree with any common-sense notions; it need *not* agree with any authorities or with the opinions of any great men (including the opinions of famous scientists); and it need *not* conform to our wishes of what we might like the world to be.

Mode of discovery: The validity of a scientific theory also does *not* depend on how, or by whom, the theory was discovered. Thus it does not

matter whether a theory was discovered as a result of careful accumulation of data, as a result of a shrewd guess, or as a result of inspiration in a dream. (Indeed, Kekulé discovered his theory of the ring structure of the benzene molecule while dreaming after falling asleep in front of his fireplace.)

In short, all of the preceding criteria are irrelevant to a scientific theory.

A scientific theory is accepted as valid *solely* on the basis of how successful it is in relating and predicting a large range of observations.	(C-1)

SECT.

D CONSTRUCTION OF THEORIES

OVERIEW

Theories are not god-given, but are invented by people. The construction of theories thus requires creativity of the same kind as artistic or other forms of human creativity. However, the extent of success of such creativity can be objectively assessed according to well-defined criteria.

CRITERIA OF A GOOD THEORY

The criteria of a good theory are implied by the scientific goal stated in Def. (A-1).

Thus the essential criterion of a successful theory is that it is valid, i.e., that it relates and predicts correctly the observations which it is designed to encompass.

Among valid theories, the best is the one which has the greatest predictive power, i.e., the one which can successfully relate and predict the largest range of observations from the smallest number of basic theoretical principles.

If two valid theories have equal predictive power, the better theory is the one which is simpler.

Theories are not necessarily unique since two different theories may account equally well for the same range of observations. However, in practice there is usually only one valid theory with great predictive power in a large domain.

METHODS FOR CONSTRUCTING THEORIES

There are no rules guaranteed to lead to the discovery of successful theories. However, it is helpful to approach the task of inventing a theory in a systematic way, considering simple cases before proceeding to more complex situations and trying to refine promising ideas by successive approximations. Quite often a few observations suggest certain tentative theoretical assumptions (called "hypotheses"). If these assumptions lead to predictions which are confirmed by many observations, these assumptions can be adopted as the basic principles of a successful theory. But if they do not lead to correct predictions, the assumptions must be modified or discarded until one arrives at assumptions which are successful for prediction.

Theories are cumulatively improved by constantly checking how well they meet the stringent criteria of good theories. Thus, if a theory is successful in predicting certain observations, it is retained or generalized so as to apply to a wider set of observations. If it is not successful, it is modified or discarded. By proceeding in this manner, one gradually obtains a few successful theories of wide generality, while the less satisfactory theories lie forgotten in library archives. In short, the development of theories successful for predicting observable phenomena is a long evolutionary process (sometimes extending over centuries). In this process new theories are constantly generated, but only those meeting the criterion of successful prediction are allowed to survive.

A successful theory predicting many observations may be superseded by a more general theory which predicts a wider range of observations. However, the earlier theory may still remain useful for dealing with the observations to which it does apply. (Indeed, both theories must somehow correspond to each other in the limited domain where both of them predict the same observations. Thus this "correspondence principle" can be used as a useful guide for the discovery of more general theories.) For example, although Einstein's theory of relativity predicts the motion of objects at all speeds, the earlier theory of Newton is still extremely useful for predicting the motion of objects moving at speeds appreciably less than the speed of light (i.e., less than 3×10^8 meter/second).

CONTRAST WITH EVERYDAY LIFE

► *Science and common sense*

In order to deal with common observations and to predict roughly what to expect in daily life, we have developed "common sense," i.e., a set of useful ideas expressed in everyday language. (For example, common sense leads us to expect that objects will fall toward the ground and that water will flow downhill.) Such common sense may be regarded as a primitive science with these limitations: (1) The language and ideas of common sense are often vague and ambiguous. (2) The predictions made on the basis of common sense are quite imprecise, nor are they tested critically against careful observations. (3) since common sense deals only with observations made in daily life, it does not extend to observations under more refined or more extreme conditions. (For example, it does not deal with observations of single atoms or of objects moving with speeds close to the speed of light.)

Thus it is not surprising that common-sense notions may, upon closer examination, be found to be utterly inadequate to deal with many observations, particularly those not encountered in daily life. Hence the ideas used in successful sciences may often differ substantially from our common-sense notions. Such ideas may thus initially seem strange when compared to our common-sense notions (which seem deceptively "natural" merely because of our long familiarity with them).

► *The meaning of explanation*

When somebody asks the question "why," he is asking for an "explanation," i.e., he is asking that the thing about which the question is asked be somehow related to something else which is more comprehensible to the questioner. In daily life, this something else is anything sufficiently acceptable to the questioner so that he stops asking further questions (e.g., some common-sense notion accepted by the questioner).

In science, a request for an explanation is understood as a request to relate something to an accepted theory. Thus "explanation" in science has this precise meaning: An explanation of some thing (observation or theoretical result) in terms of some specified theory is a demonstration that the thing can be predicted on the basis of this theory.

SECT.

E SCOPE AND LIMITATIONS OF SCIENCE

OVERVIEW

Science, with its concern for relating and predicting observations, is only one of many worthwhile activities. Thus there are many other activities which have a different focus of interest. For example, pure mathematics is completely unconcerned with observations, but is only interested in the study of symbolic relationships. (Of course, this study may ultimately be found useful in the theoretical structures of some sciences.) Similarly, poetry is a legitimate activity that uses language for purposes quite unrelated to the prediction of observations.

Since various human concerns often get intermingled, it is important to distinguish clearly between those concerns which are scientific and those which are not. The dangers of confusion are particularly great since science itself leads often to consequences which are outside the realm of science.

CONSEQUENCES OF SCIENCE

A successful science achieves the ability to predict reliably a large range of observations. Hence it makes it possible for man to control events according to chosen goals. The question of how these goals are chosen can have very important consequences. Yet this question goes beyond the realm of predicting observations and is thus outside of science. (For example, the successful development of chemistry allows one to predict the occurrence of certain chemical reactions accompanied by a rapid release of much energy. Accordingly, it becomes possible to make explosives such as dynamite. But then there arises the question of choosing whether such explosives will be used for building roads or for killing people in war.)

The choices made in the use of science present very difficult problems. Such problems continually arise and are often unexpected since it is almost impossible to predict the results of purely scientific inquiry. (For example, nobody ever suspected that the investigation of electric currents in gases would lead to the discovery of x-rays with all their subsequent beneficial applications in medicine and dangers to human health.) Furthermore, since the ever-increasing predictive power achieved by scientific progress makes it possible to shape events on an ever larger scale, the choices made in the use of science can today have consequences affecting the very survival of mankind.

SCIENTIFIC AND NONSCIENTIFIC ASPECTS OF PROBLEMS

Most problems facing us in real life involve human goals and thus raise both scientific and non-scientific questions. For example, the following scientific questions are usually pertinent: (1) What are the observed facts and the relations between them? (2) What are the alternative possible courses of action? (3) What are the predicted consequences of these alternative actions? The non-scientific questions of choice (or "value" questions) are: On the basis of this information, what kind of choices should be made and by whom?

To give a trivial example, biomedical science can indicate several alternative diets consisting of various kinds of food. It can also predict the consequences to health of these various diets. But the ultimate choice based on this information depends on non-scientific considerations involving human values. Thus someone might well prefer the choice of eating many fattening foods and living less long.

Problems involving consequences for the entire society are, of course,much more complex. Knowing the scientifically available alternatives for electric energy generation and the predicted consequences of these, should one choose (and who should decide) to have more plentiful energy from the use of nuclear fuels and greater risks of many deaths from dangerous radioactivity?

The preceding comments should suffice to indicate that most real problems in this world are quite complex and not amenable to simplistic thinking. They usually demand a careful analysis both of their scientific aspects and of the values underlying questions of choice.