From Introductory Physics: A Model Approach by Robert Karplus, 2nd Edition (F. Brunschwig, Editor).

1.3 Theories and models in science

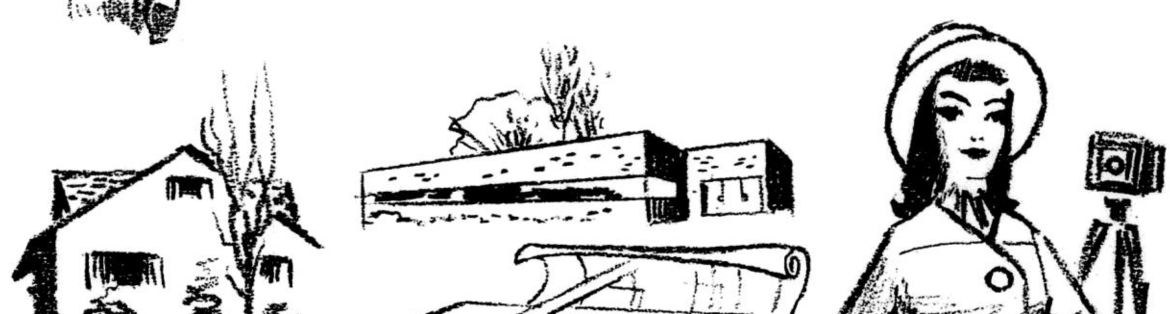
In the preceding section we contrasted the roles played in science by observation and interpretation. Observations of experimental outcomes provide the raw data of science. Interpretations of the data relate them to one another in a logical fashion, fit them into larger patterns, raise new questions for investigation, and lead to predictions that can be tested.

Scientific theories are systematically organized interpretations. Examples are Dalton's atomic theory of chemical reactions, Newton's theory of universal gravitation, Einstein's theory of relativity, and Piaget's theory of intellectual development. Within the framework of a scientific theory, observations can be interpreted in much more far-reaching ways than are possible without a theory. In Newton's theory of gravitation, for instance, data on the orbital motion of the moon lead to a numerical value for the total mass of the earth! In Dalton's theory, the volumes of chemically reacting gases lead to the chemical formulas for the compounds produced. All theories interrelate and extend the significance of the facts that fall within their compass.

Working models. Theories frequently make use of simplified mental images for physical systems. These images are called *working models* for the system. One example is the sphere model for the earth, in which the planet is represented as a uniform spherical body and its topographic and structural complexities are neglected. Another example is the particle model for the sun and planets in the solar system; in this model each of these bodies is represented as a simple massive point in space, and its size as well as its structure is ignored. Still another example is the "rigid body model" for any solid object (a table, a chair) that has a definite shape but may bend or break under a great stress.

Unlike other kinds of models (Fig. 1.3), a working model is an abstraction from reality. Our thoughts can never comprehend the full complexity of all the details of an actual system. Working models are always simplified or idealized representations, as we have already pointed out. Working models, therefore, and the theories of which they are a part, have limitations that must be remembered when their theoretical predictions fail to agree with observations.

Figure 1.3 The word "model" has many connotations in the English language, and most of them are not applicable to the scientific meaning of the word. A scientific "working model" has very little in common with a scale model (model airplane, left), a sample for examination (model home, below left), a visual replica (architectural model, below center), or a person (artist's or fashion model, below right).



The scientist's relationship to the models he constructs is ambivalent. On the one hand, the invention of a model engages his creative talent and his desire to represent the operation of the system he has studied. On the other hand, once the model is made, he seeks to uncover its limitations and weaknesses, because it is from the model's failures that he gains new understanding and the stimulus to construct more effective models. Both creative and critical faculties are involved in the scientist's work with models.

One feature of working models is frequently disturbing to nonscientists: no model perfectly matches reality, and you never know whether a particular model is "right." In fact, the concepts "right" and "wrong" do not really apply to models. Instead, a model may be more or less adequate, depending on how well it represents the functioning of the system it is supposed to represent. Even an inadequate model is better than none at all, and even a very adequate model is often replaced by a still more adequate one. The investigator has to determine whether a particular model is good enough for his purposes or whether it is necessary to seek a better one.

Analogue models. Before a scientist constructs a theory, he often realizes that the system he is studying operates in a way similar to another system with which he is more familiar, or on which he can conduct experiments more easily. This other system is called an analogue model for the first system. You may, for instance, liken the spreading out of sound from a violin to the spreading out of ripples from a piece of wood bobbing on a water surface.

The analogue model for one physical System A is another, more familiar, System B, whose parts and functions can be put into a simple correspondence with the parts and functions of System A. For example, an analogy may be drawn between the human circulatory system and a residential hot water heating system (Table 1.1, below). It is clear that

TABLE 1.1 ANALOGUE MODEL FOR THE HUMAN CIRCULATORY SYSTEM

System A: Human circulatory system	**System B:** Residential hot water heating system
veins, arteries	pipes
blood	water
oxygen	thermal energy
heart	pump
lungs	furnace
capillaries	radiators
hormones	thermostat
(model fails)	overflow tank
(or dilation of veins & arteries)	
blood pressure	water pressure
white blood cells	(model fails)
carbon dioxide	(model fails)
kidneys	(model fails)
intestine	(model fails)

the human circulatory system fulfills several functions, whereas the heating system fulfills only one. The analogue model is, therefore, not complete, but it is nevertheless instructive.

The virtue of an analogue model is that System B is more familiar than System A. This familiarity can have several advantages:

1. Features of the analogue model can call attention to overlooked features of the original system. (Had you overlooked the role of hormones in the circulatory system, the room thermostat would have reminded you.)
2. Relationships in the analogue model suggest similar relationships in the original system. (Furnace capacity must be adequate to heat the house on a cold day; lung capacity must be adequate to supply oxygen needs during heavy exercise.)
3. Predictions about the original system can be made from known properties of the more familiar analogue model. (Water pressure is high at the inflow to the radiators, low at the outflow; therefore, blood pressure is high in the arteries, low in the veins.)

The limitations of the analogue model can lead to erroneous conclusions, however. On a cold day, for instance, the water temperature is higher in the radiators; therefore, you might predict that the oxygen concentration in the blood will be higher during heavy exercise. Actually, the heartbeat and the rate of blood flow increase to supply more oxygen - the oxygen concentration does not change greatly.

"There are two methods in which we acquire knowledge - argument and experiment."
Roger Bacon (1214-1294)

Thought experiments. In a thought experiment, a model is operated mentally, and the consequences of its operation are deduced from the properties of the model. A thought experiment differs from a laboratory experiment in that the latter serves to provide new information about what really happens in nature, whereas the former seeks new deductions from previous knowledge or from assumptions. By comparing the deductions with observations in real experiments, you can find evidence to support or contradict the properties or assumptions of the model.

A simple example of a mystery system (Fig. 1.4) can be used to illustrate these ideas. Two working models for what might be under the cover in Fig. 1.4 (a) are shown in Figs. 1.4 (b) and (c). If you conduct simple thought experiments with these models, you quickly find out how satisfactory they are. In the first thought experiment, you imagine turning handle A clockwise. In model G, handle B will turn somewhat faster, because the second gear is smaller than the first, but it will turn counterclockwise. This prediction is in disagreement with the properties of the mystery system. In the second thought experiment, you turn handle A in model S. What can you infer from this second experiment? Can you suggest a satisfactory working model?

Thought experiments are important tools of the theoretical scientist because they enable him to make deductions from a working model or a theory. These deductions can then be compared with observation. The usefulness of a theory or model is determined by the agreement between the deduction and observation. Some very general theories,

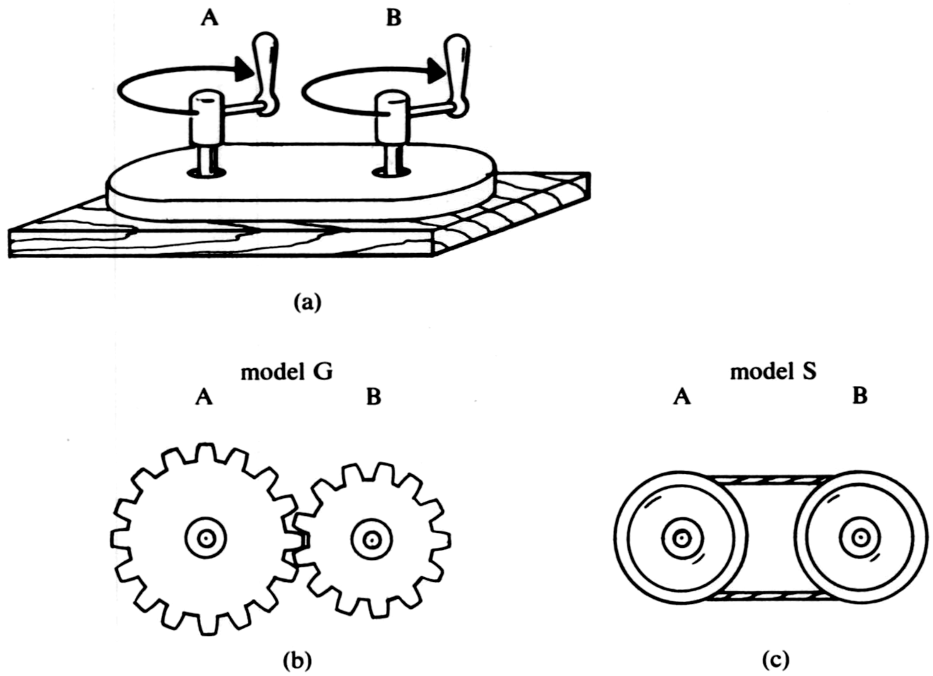


Figure 1·4 A mystery system. (a) When handle A is turned one revolution clockwise, handle B makes 2½ revolutions clockwise. Make models for what is under the cover. (b) Large and small gear model. (c) Two pulley and string model.

Equation 1.1

Mathematical model (algebraic form):
number of turns of handle A = N_A
number of turns of handle B = N_B

$$N_A = N_B$$

Equation 1.2

Mathematical model (algebraic form):
distance $= s$
speed $= v$
time $= t$

$$s = vt$$

such as the theory of relativity, lead to consequences that appear to apply universally. Some models, such as the corpuscular model for light, are useful only in a very limited domain of phenomena.

Mathematical models and variable factors. Scientific theories are especially valuable if they lead to successful quantitative predictions. Working models G and S for the mystery system in Fig. 1.4 both lead to quantitative predictions for the relationship between the number of turns of handles A and B. The relationship deduced from model S (that the handles turn equally) can be represented by the formula in Equation 1·1. We will call such relationships *mathematical models;* the formula in Equation 1.1 is an algebraic way of describing the relationship, which we have also described in words, and which can be described by means of a graph (Fig. 1.5).

A familiar example of a mathematical model, applicable to an automobile trip, is the relation of the distance traveled, time on the road, and speed of the car (Equation 1.2). The distance is equal to the speed times the time. At 50 miles per hour, for example, the car covers 125 miles in 2 ½ hours (Fig. 1.6).

The physical quantities related by a mathematical model are called *variable factors* or *variables*. The numbers of turns of handles A and B are two variable factors in Equation 1.1 and Fig. 1.5. The distance and elapsed time are two variable factors in Equation 1.2 and Fig. 1.6, The speed in this

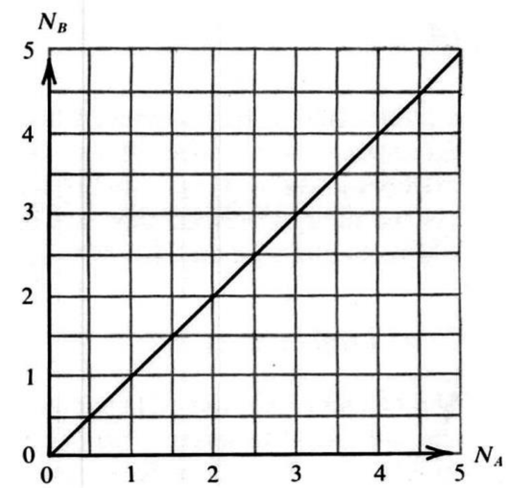


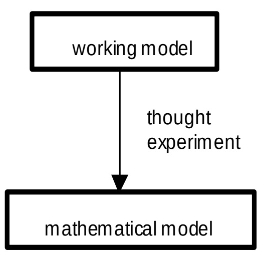
Figure 1.5 Mathematical model (graphical form).

Number of turns of handle A = N_A*;*

Number of turns of handle B = N_B*;*

mathematical model is called a constant, because it does not vary. Under different conditions, as in heavy traffic, the speed might be a variable factor.

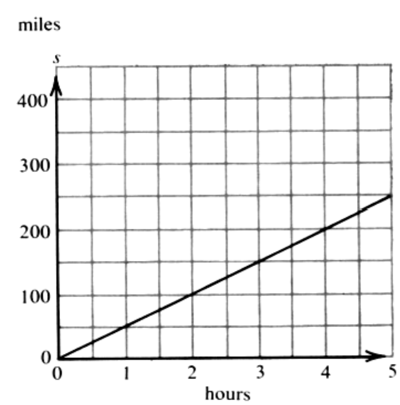
Like the working model for a system, the mathematical model for a relationship is not an exact reproduction of a real happening. No real car, for instance, should be expected to travel at the perfectly steady speed of 50 miles per hour for 2½ hours. The actual speed would fluctuate above and below the 50-mile figure. The actual distances covered at various elapsed times, therefore, might be a little more or a little less than those predicted by the model in Eq. 1.2 and Fig. 1.6. Nevertheless, the model gives a very good idea of the car's progress on its trip, and it is very simple to apply. For these reasons, the model is extremely useful, but you must remember its limitations.



Scientific theories. The making of a physical theory often includes the selection of a working model, the carrying out of thought experiments, and the construction of a mathematical model. All physical theories have limitations imposed by the inadequacies of the working model and the conditions of the thought experiments. Occasionally a theory has to be

Figure 1.6 Mathematical model of relationship between distance and time (graphical form):

Distance = s (miles),
time = t (hours),
speed = 50 miles per hour.



abandoned because it ceases to be in satisfactory agreement with observations. Nevertheless, physical theories are extremely useful. It is probably the power of the theory-building process we have described that lies behind the rapid progress of science and technology in the last 150 years.