Chapter two

Basic Concepts

2.1 Definition of terms

2.1.1 Readability:

This term indicates that the grade of the scale is of the instrument is readable. An instrument with a 12-in scale would have a higher readability than an instrument with a 6-in scale for the same range. The least count is the smallest difference between two indications that can be detected on the instrument scale. Both readability and least count are dependent on scale length, spacing of graduations, size of pointer (or pen if a recorder is used), and parallax effects.

For an instrument with a digital readout the terms “readability” and “least count” have little meaning. Instead, one is concerned with the display of the particular instrument.

2.1.2 Sensibility:

The sensitivity of an instrument is the ratio of the linear movement of the pointer on an analog instrument to the change in the measured variable causing this motion. For example, a 1-mV recorder might have a 25-cm scale length. Its sensitivity would be 25 cm/mV, assuming that the measurement was linear all across the scale. For a digital instrument readout the term “*sensitivity*” does not have the same meaning because different scale factors can be applied with the push of a button.

2.1.3 Hysteresis

An instrument is said to exhibit *hysteresis* when there is a difference in readings depending on whether the value of the measured quantity is approached from above or below. Hysteresis may be the result of mechanical friction, magnetic effects, elastic deformation, or thermal effects.

2.1.4 Accuracy

The accuracy of an instrument indicates the deviation of the reading from a known input. Accuracy is frequently expressed as a percentage of full-scale reading, so that a 100-kPa pressure gage having an accuracy of 1 percent would be accurate within ±1 kPa over the entire range of the gage. In other cases accuracy may be expressed as an absolute value, over all ranges of the instrument.

2.1.5 Precision

It indicates its ability to reproduce a certain reading with a given accuracy. As an example of the distinction between precision and accuracy, consider the measurement of a known voltage of 100 V with a certain meter. Four readings are taken; 104, 103, 105, and 105 V. From these values it is seen that the instrument could not be depended on for an accuracy of better than 5 percent (5 V), while a precision of ±1 percent is indicated since the maximum deviation from the mean reading of 104 V is only 1 V. It may be noted that the instrument could be calibrated so that it could be used dependably to measure voltages within ±1 V. Accuracy can be improved up to but not beyond the precision of the instrument by calibration. The precision of an instrument is usually subject to many complicated factors and requires special techniques of analysis.

2.1.6 Uncertainty

We should alert the reader to some data analysis terms. *Accuracy* has already been mentioned as relating the *deviation* of an instrument reading from a *known value*. The deviation is called the *error*. In many experimental situations we may not have a known value with which to compare instrument readings, and yet we may feel fairly confident that the instrument is within a certain plus or minus range of the true value. In such cases we say that the plus or minus range expresses the *uncertainty* of the instrument readings. Many experimentalists are not very careful in using the words “*error*” and “*uncertainty*”.

2.2 Calibration

The calibration of all instruments is important, for it affords the opportunity to check the instrument against a known standard and subsequently to reduce errors in accuracy. Calibration procedures involve a comparison of the particular instrument with either (1) a primary standard, (2) a secondary standard with a higher accuracy than the instrument to be calibrated, or (3) a known input source.

For example, a flowmeter might be calibrated by (1) comparing it with a standard flow-measurement facility of the National Institute for Standards and Technology (NIST), (2) comparing it with another flowmeter of known accuracy, or (3) directly calibrating with a primary measurement such as weighing a certain amount of water in a tank and recording the time elapsed for this quantity to flow through the meter.

The importance to emphasize the calibration because the calibration establishes the accuracy of the instruments. It is usually best to make at least a simple calibration check to be sure of the validity of the measurements. Not even manufacturers' specifications or calibrations can always be taken at face value. Most instrument manufacturers are reliable; some, alas, are not.

2.3 Standards

In order that investigators in different countries and different locations of the world may compare the results of their experiments on a consistent basis, it is necessary to establish certain standard units of length, weight, time, temperature, and electrical quantities. NIST has the primary responsibility for maintaining these standards in the United States.

2.4 Dimensions and units

Despite strong emphasis in the professional engineering community on standardizing units with an international system, a variety of instruments will be in use for many years, and an experimentalist must be conversant with the units which appear on the gages and readout equipment. The main difficulties arise in mechanical and thermal units because electrical units have been standardized for some time. It is hoped that the SI (System International Unites) set of units will eventually be dominant. Although the SI system is preferred, one must recognize that the English system is still very popular.

One must be careful not to confuse the meaning of the term "units" and "dimensions." A dimension is a physical variable used to specify the behavior or nature of a particular system. For example, the length of a rod is a dimension of the rod. In like manner, the temperature of a gas may be considered one of the thermodynamic dimensions of the gas. When we say the rod is so many meters long, or the gas has a temperature of so many degrees Celsius, we have given the units with which we choose to measure the dimension.

L = length, M = mass, F = force, τ = time, T = temperature

All the physical quantities used may be expressed in terms of these fundamental dimensions. The units to be used for certain dimensions are selected by somewhat arbitrary definitions which usually relate to a physical phenomenon or law.

Quantity	**Unit**	**Symbol**
	Basic units	
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K

2.5 The generalized measurement system

Most measurement systems may be divided into three parts:

1. *A detector-transducer stage*, which detects the physical variable and performs either a mechanical or an electrical transformation to convert the signal into a more usable form. In the general sense, a transducer is a device that transforms one physical effect into another. In most cases, the physical variable is transformed into an electric signal

because this is the form of signal that is most easily measured. The signal may be in digital or analog form. Digital signals offer the advantage of easy storage in memory devices, or manipulations with computers.

2. *Some intermediate stage*, which modifies the direct signal by amplification, filtering, or other means so that a desirable output is available.
3. *A final or terminating stage*, which acts to indicate, record, or control the variable being measured. The output may also be digital or analog.

As an example of a measurement system, consider the measurement of a low voltage signal at a low frequency. The detector in this case may be just two wires and possibly a resistance arrangement, which are attached to appropriate terminals. Since we want to indicate or record the voltage, it may be necessary to perform some amplification. The amplification stage is then stage 2, designated above. The final stage of the measurement system may be either a voltmeter or a recorder that operates in the range of the output voltage of the amplifier. An electronic voltmeter is a measurement system. The amplifier and the readout voltmeter are contained in one package, and various switches enable the user to change the range of the instrument by varying the input conditions to the amplifier.

Another example, the simple bourdon-tube pressure gage. This gage offers a mechanical example of the generalized measurement system. In this case, the bourdon tube is the detector-transducer stage because it converts the pressure signal into a mechanical displacement of the tube. The intermediate stage consists of the gearing arrangement, which amplifies the displacement of the end of the tube so that a relatively small displacement at that point produces as much as three-quarters of a revolution of the center gear. The final indicator stage consists of the pointer and the dial arrangement, which, when calibrated with known pressure inputs, gives an indication of the pressure signal impressed on the bourdon tube. See Figure 2.1 and 2.2.

2.6 Basic concepts in dynamic measurement

A *static* measurement of a physical quantity is performed when the quantity is not changing with time. The deflection of a beam under a constant load would be a static deflection. However, if the beam were set in vibration, the deflection would vary with time, and the measurement process might be more difficult. Measurements of flow processes are much easier to perform when the fluid is in a steady state and become progressively more difficult to perform when rapid changes with time are encountered.

Many experimental measurements are taken under such circumstances that time is available for the measurement system to reach steady state, and hence one need not be concerned with the behavior under non-steady-state conditions. In many other situations, it may be desirable to determine the behavior of a physical variable over a period of time. Sometimes the time interval is short, and sometimes it may be rather extended. In any event, the measurement problem usually becomes more complicated when the transient characteristics of a system need to be considered.

2.7 Experiment planning

The key to success in experimental work is to ask continually: What am I looking for? Why am I measuring this? Does the measurement really answer any of my questions? What does the measurement tell me?

These questions may seem rather elementary, but they should be asked frequently throughout the progress of any experimental program. Some particular questions that should be asked in the initial phases of experiment planning are:

1. What primary variables shall be investigated?

2. What control must be exerted on the experiment?

3. What ranges of the primary variables will be necessary to describe the phenomena under study?

4. How many data points should be taken in the various ranges of operation to ensure good sampling of data considering instrument accuracy and other factors?

5. What instrument accuracy is required for each measurement?

6. If a dynamic measurement is involved, what frequency response must the instrument have?

7. Are the instruments available commercially, or must they be constructed especially for the particular experiment?

8. What safety precautions are necessary if some kind of hazardous operation is involved in the experiment?

9. What financial resources are available to perform the experiment, and how do the various instrument requirements fit into the proposed budget?

10. What provisions have been made for recording the data?

11. What provisions have been made for either on-line or subsequent computer reduction of data?

12. If the data reduction is not of a “research” nature where manipulation and calculations depend somewhat on the results of measurements, what provisions are made to have direct output of a data acquisition system available for the final report? In many cases appropriate graphical results may be obtained with digital data acquisition systems as the experiment progresses or shortly thereafter.

The importance of the control in any experiment should always be recognized. The physical principle, apparatus, or device under investigation will detect the variables which must be controlled carefully. For example, a heat-transfer test of a particular apparatus might involve some heat loss to the surrounding air in the laboratory where the test equipment is located. Consequently, it would be wise to maintain (control) the surrounding temperature at a reasonably constant value. If one run is made with the room temperature at 90◦C and another at 10◦C, large unwanted effects may occur in the measurements.

Therefore, we make a series of measurements of the characteristics of a device under certain specified operating conditions–no comparison with other devices is made. Whenever a comparison test is performed to establish relative performance, control must be exerted over more than one experimental setup in order for the comparison to be significant.

It would seem obvious that a care should be made to record the data and all ideas and observations concerned with the experiment. Yet, many experimenters record data and important sketches on pieces of scratch paper or in such a disorganized manner that they may be lost or thrown away. In some experiments, the readout instrument is a recording type so that a record is automatically obtained and there is little chance for loss. For many experiments, visual observations must be made and values recorded on an appropriate data sheet. This data sheet should be very carefully planned so that it may subsequently be used, if desired, for data reduction. Frequently, much time may be saved in the reduction process by eliminating unnecessary transferal of data from one sheet to another. If a computer is to be used for data reduction, then the primary data sheet should be so designed that the data may be easily transferred to the input device of the computer. Even with digital readout systems the printout must be carefully labeled, either in the machine programming or by hand.

A *bound notebook* should be maintained to record sketches and significant observations of an unusual character which may occur during both the planning and the execution stages of the experiment. Do not take this item lightly. A great amount of money is wasted by individuals who rush into a program only to discover later that the experiments were unnecessary for their own particular purposes.

2.8 Generalized experimental procedure

1. Establish the need for the experiment.

2. Establish the optimum budgetary, manpower, and time requirements, including time sequencing of the project. Modify scope of the experiment to actual budget, manpower, and time schedule which are allowable.

3. Begin detail planning for the experiment; clearly establish objectives of experiment (verify performance of production model, verify theoretical analysis of particular physical phenomenon, etc.). If experiments are similar to those of previous investigators, be sure to make use of experience of the previous workers. Never overlook the possibility that the work may have been done before and reported in the literature.

4. Continue planning by performing the following steps:

a. Establish the primary variables which must be measured (force, strain, flow, pressure, temperature, etc.).

b. Determine as nearly as possible the accuracy which may be required in the primary measurements and the number of such measurements which will be required for proper data analysis.

c. Set up date reduction calculations before conducting the experiments to be sure that adequate data are being collected to meet the objectives of the experiment.

d. Analyze the possible errors in the anticipated results before the experiments are conducted so that modifications in accuracy requirements on the various measurements may be changed if necessary.

4. Select instrumentation for the various measurements to match the anticipated accuracy requirements. Modify the instrumentation to match budgetary limitations if necessary.

5. Collect few data points and conduct a preliminary analysis of these data to be sure that the experiment is going as planned.

6. Modify the experimental apparatus and/or procedure in accordance with the findings in item 5.

7. Collect the bulk of experimental data and analyze the results.

8. Organize, discuss, and publish the findings and results of the experiments, being sure to include information pertaining to all items 1 to 7, above.

2.9 The Role of Uncertainty Analysis in Experiment Planning

There is a need to perform preliminary analyses of experimental uncertainties in order to effect a proper selection of instruments and to design the apparatus to meet the overall goals of the experiment. Recall our previous comments about the terms *accuracy*, *error*, and *uncertainty*. We noted that many persons use the term “error” when “*uncertainty*” is the proper nomenclature.

It is clear that certain variables being measured are set by the particular experimental objectives, but there may be several choices open in the method to measure these variables. An electric-power measurement could be performed by measuring current and voltage and taking the product of these variables. The power might also be calculated by measuring the voltage drop across a known resistor, or possibly through some calorimetric determination of the heat dissipated from a resistor. The choice of the method used can be made on the basis of an uncertainty analysis, which indicates the relative accuracy of each method. A flow measurement might be performed by sensing the pressure drop across an obstruction meter, or possibly by counting the number of revolutions of a turbine placed in the flow. In the first case the overall uncertainty depends on the accuracy of a measurement of pressure differential and other variables, such as flow area, while in the second case the overall uncertainty depends on the accuracy of counting and a time determination.

The point is that a careful uncertainty analysis during the experiment planning period may enable the investigator to make a better selection of instruments for the program. Briefly, an uncertainty analysis enters into the planning phase with the following approximate steps:

1. Several alternative measurement techniques are selected once the variables to be measured have been established.

2. An uncertainty analysis is performed on each measurement technique, taking into account the estimated accuracies of the instruments that will actually be used.

3. The different measurement techniques are then compared on the basis of cost, availability of instrumentation, ease of data collection, and calculated uncertainty. The technique with the least uncertainty is clearly the most desirable from an experimental-accuracy standpoint, but it may be too expensive. Frequently, however, the investigator will find the cost is not a strong factor and that the technique with the smallest uncertainty (within reason) is as easy to perform as some other less accurate method.

The following Figure divides the procedure of section 2.8 into a graphical pattern of preliminary, intermediate, and final stages of an experimental program. The feedback blocks in these diagrams are very important because they illustrate the need to retrace continuously one's steps and modify the program in accordance with the most current information that is available.

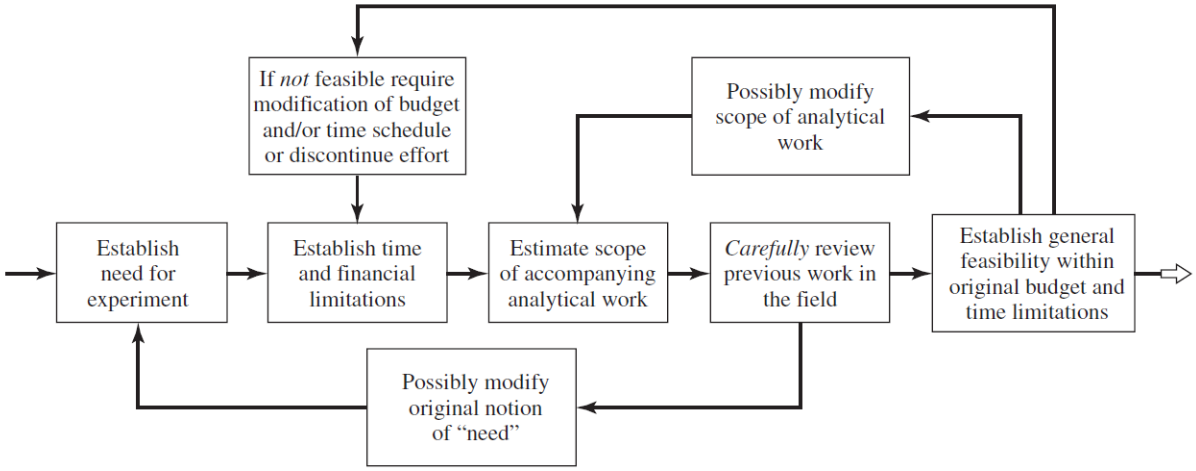

Figure 2-1. Preliminary stages of experiment planning.

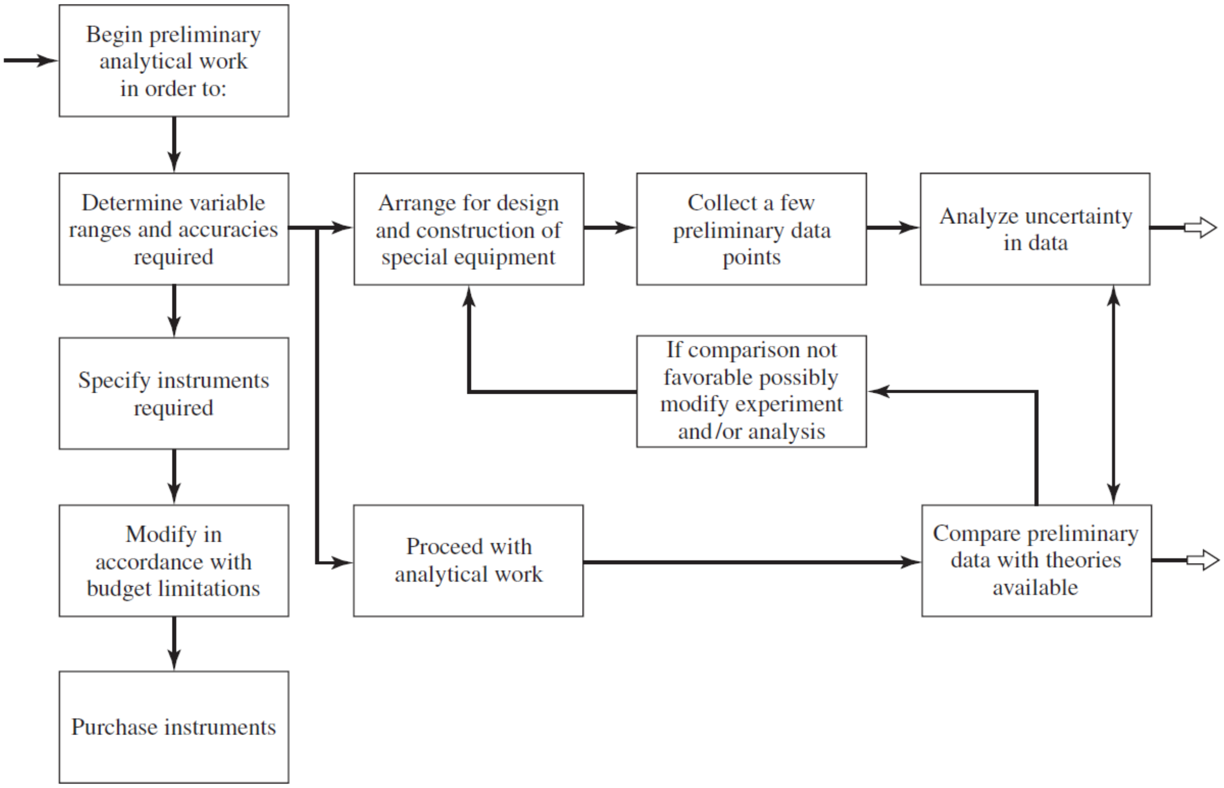

Figure 2-2. Intermediate stages of experiment planning.

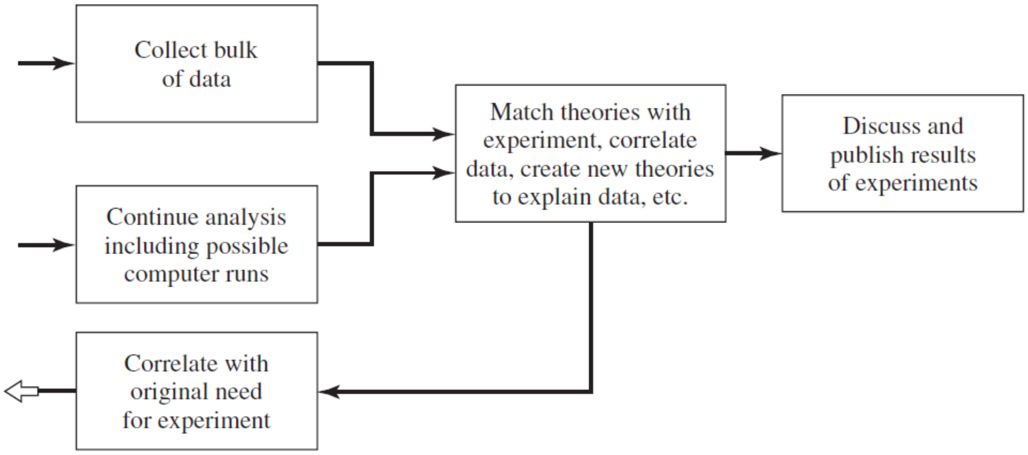

Figure 2-3. Final stages of experimental program.