Introduction to Engineering Measurement

> "When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science." — Lord Kelvin

How good is a program? How reliable will a software system be once it is installed? How much more testing should I do? How many more bugs can I expect to find? How much will the testing cost? How difficult will it be to maintain a system? How much will it cost to build a new system similar to one we built five years ago? How long will it take?

Software engineers face questions like these every day of their professional lives. At the heart of these questions is one of the most important concepts in engineering: measurement. An engineer needs to know why to make measurements, what can be measured, what should be measured, how to measure, and what to do with the results. Let's explore these issues in the general context of science and engineering.

1. Definitions

The first question might be, "What is measurement?" In its simplest form, we can think of measurement as associating a numeric value with an object or action. We interpret that value as the amount of some quality or attribute possessed by that object or action.

If we look in dictionaries and technical glossaries, we find definitions like these:

measure	(verb) To ascertain the quantity, mass, extent, or degree of something in terms of a standard unit or fixed amount, usually by means of an instrument or process; to compute the size of something from dimensional measurements; to estimate the extent, strength, worth, or character of something; to take measurements.

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	(noun) A standard or unit of measurement; the extent, dimensions, capacity, etc. of anything, especially as determined by a standard; an act or process of measuring; a result of measurement.
measurement	The act or process of measuring something. Also a result, such as a figure expressing the extent or value that is obtained by measuring.

These definitions are very general and abstract. We can perhaps gain a better understanding of measurement by looking at examples from the everyday physical world.

2. Measures in the Physical World

The materials and forces of the physical world are the raw materials of the traditional engineering disciplines (such as civil, mechanical, electrical, and chemical engineering). Measuring in the physical world is thus a basic skill needed by engineers.

There are only a few fundamental physical measures. The most common of these are length, mass, and time. Other measures can be expressed in terms of these; for example, we express the speed of our cars in miles per hour (length divided by time), or our weight (which is really a measure of the force of gravity on our bodies at the earth’s surface) in pounds (mass times length divided by time squared).

There can be many different units of measurement for a given physical measure. For example, we can measure length in meters, kilometers, inches, miles, and light-years, and we can measure time in seconds, minutes, hours, and years.

Discussion Question 1

Measurement of length almost certainly predates historical records. The earliest measures were probably in terms of the human body, and some of those measures survive to this day. The most obvious example is the *foot*. What are some other such measures? (This question may be easier if you have had occasion to measure horses or whiskey.) What is a *cubit?*

The most common set of measures is the *metric system*, used throughout the world, except in the United States, where the *English system* is more common. (Note that the English system of measures in no longer the official system in England!) The seven base units of measurement in the metric system are:

Unit	**Entity Measured**
meter	length
kilogram	mass
second	time
ampere	electric current
kelvin	thermodynamic temperature
mole	number of particles
candela	light intensity

A standard vocabulary of prefixes has been defined in order to measure very large and very small quantities. These are shown in Figure 1.

Prefix	**Symbol**	$\times 10^n$	**Prefix**	**Symbol**	$\times 10^n$
deka-	da	1	deci-	d	-1
hecto-	h	2	centi-	c	-2
kilo-	k	3	milli-	m	-3
mega-	M	6	micro-	μ	-6
giga-	G	9	nano-	n	-9
tera-	T	12	pico-	p	-12
peta-	P	15	femto-	f	-15
exa-	E	18	atto-	a	-18
zetta-	Z	21	zepto-	z	-21
yotta-	Y	24	yocto-	y	-24

Figure 1. Metric system measurement prefixes

Discussion Question 2

What are some common units of measure that use the prefixes in Figure 1? What is another term for one one-millionth of a meter, and why is a machinist likely to prefer it to *micrometer?* Why is the term *decibel*, a unit of loudness, much more common than the whole unit, the *bel?*

Research Question 3

What reasoning might have been used to choose the names of the prefixes in the metric system? Do the words mean anything? Hint: What are the Greek words for *ten*, *hundred*, and *thousand?* What are the Latin words? What are the Danish or Norwegian words for *fifteen* and *eighteen?* What is an Italian word for *small?* What are Greek words for *small*, *large*, *giant*, *dwarf*, and *monster?*

Research Question 4

What do the terms *megaflops* and *gigalips* denote? Hint: These do not refer to Hollywood movies that lose millions of dollars or to a medical condition. Another hint: They do refer to computer performance.

Discussion Question 5

What are some real-world entities that are measured in units using some of the more extreme prefixes? For example, is a typical human life span closer to a megasecond, gigasecond, or terasecond? How far does light travel in a microsecond, a nanosecond, or a picosecond? What two places are about a megameter apart? A terameter apart? Which is larger, a zettameter or the diameter of the Milky Way galaxy? Is the mass of an electron more or less than a yoctogram?

Digression. Helen of Troy is said to have been the most beautiful woman of the ancient world, and her abduction to Troy was the major cause of the Trojan War. The Greeks needed hundreds of ships to transport their soldiers to Troy, so it is sometimes said that Helen had the face that launched a thousand ships. Beauty is a difficult thing to measure, but the legend of Helen of Troy provides one possible solution. We can choose as our unit of measure the *millihelen*, which is defined as the precise amount of beauty necessary to launch exactly one ship.

In science and engineering, we usually choose to use the *mks* system (meter-kilogram-second), the *cgs* system (centimeter-gram-second), or the *fps* system (foot-pound-second). Each of these systems of measures includes a variety of other measures that can be expressed in terms of the basic measures.

Research Question 6

The last four centuries have produced many scientists who made important contributions to our understanding of the physical world, and several of these scientists have been honored by having units of measure named for them. Identify the following scientists, the unit (or scale) of measure named for them, the kind of measure it is, and its definition in terms of the fundamental measures.

André-Marie Ampère
Anders J. Ångström
Amedeo Avogadro
Alexander Graham Bell
Anders Celsius (scale)
Charles A. de Coulomb
Marie Curie and Pierre Curie
Gabriel D. Fahrenheit (scale)
Michael Faraday (2 answers)
Enrico Fermi
Karl Friedrich Gauss
Joseph Henry
Heinrich R. Hertz
James P. Joule
William Thomson, Lord Kelvin
James Clerk Maxwell
Friedrich Mohs (scale)
Isaac Newton
Hans Christian Ørsted
Georg Simon Ohm (2 answers)
Blaise Pascal
Charles R. Richter (scale)
Wilhelm Röntgen
Nikola Tesla
Allesandro Volta
James Watt
Wilhelm E. Weber

3. What Engineers Measure

Engineering is often described as being a process that results in useful products. It follows that we can describe what engineers measure in two broad categories: *product* measures and *process* measures.

We can further categorize the product measures as *static* and *dynamic*. Many of the physical measures of objects—such as size, length, height, width, weight, capacity, and volume—are static, meaning that they can usually be measured while the object is not in use. The dynamic measures describe the behavior of the object while it *is* in use; these include such attributes as velocity, fuel or power consumption, heat dissipation, vibration, and noise level. Engineers in the various disciplines (civil, mechanical, electrical, chemical, etc.) typically need to know dozens of specialized static and dynamic measures for the kinds of products they build.

The process measures are used to quantify the human activity of engineering, and they are much more alike across the various engineering disciplines than are the product measures. They typically include staff size, effort, calendar time, costs, and productivity. The importance of these measures is best understood by remembering that engineering activity in our society is subject to economic constraints. Whether the engineering is done by a private, profit-oriented company or by public, tax-supported engineers, the success of the project almost always depends on achieving the desired results on time and within budget.

We also characterize some measures as being *basic* or *directly measurable* quantities, and others as *composite* or *derived* quantities. Quantities like length, time, and weight are usually measured directly, while measures of productivity and velocity are often derived from direct measures by a mathematical operation (productivity can be computed by dividing the number of items produced by the time it took to produce them; velocity can be computed by dividing the distance traveled by the time it took).

4. Why Engineers Measure

There are several reasons why engineers measure. Let’s look at the most important ones.

1. To describe the current state of the world

In one sense, every measurement describes an aspect of the *current* state of the world—a measurement made today describes something today, not how it was yesterday or how it will be tomorrow. But we know that things change over time, both in the physical world and in the software engineering world. If we can measure the current state of the world from time to time, it is often possible to discover *patterns* and *trends*.

The discovery of patterns in nature has always been one of the fundamental goals of science. Scientific explanations of the behavior of the physical world, what we often call *scientific theories* or *laws*, are almost always suggested by the results of measurements.

Once a theory has been formed, additional measurements can be made that support or refute the theory, thereby leading to a modified or improved theory.

A famous example of the relationships between theory and empirical measurement comes from the late 16th century. Johannes Kepler was attempting to describe the apparent motions of the planets with simple mathematical formulas, but without success. Only after he gained access to the Danish astronomer Tycho Brahe's substantially more accurate measurements of the positions of the planets did the ellipse suggest itself as the shape of the orbits. Kepler's theory provided a way of predicting the position of a planet at a specific time in the future, and other astronomers were able to make measurements that further supported the theory. Kepler's theory, when written as mathematical formulas, has come to be known as Kepler's laws.

Engineers are less often concerned with discovering the fundamental laws of nature than they are with discovering the behavior of the systems they design and build. They also may be concerned with trends in the engineering process itself. Measurements taken over time can help in both areas.

Discussion Question 7

What measures of the current state of your world do you make periodically? What trends are you trying to identify?

2. To state requirements quantitatively and demonstrate compliance

It is almost impossible to imagine an engineering project without quantitative requirements. A civil engineer designing a highway bridge over a river is concerned with the length of the bridge, the maximum traffic load, the height and flow of the river at flood stage, the maximum wind load the bridge must withstand, etc. An engineer designing appliances and small consumer products may be concerned with size, weight, cost, and power dissipation. An automotive engineer will have requirements of size, weight, power, passenger space, luggage space, emissions, and crash resistance. All of these requirements are likely to be expressed quantitatively. When the engineer wants to demonstrate that a product or system satisfies quantitative requirements, measurement is necessary.

Software engineers also work with quantitative requirements. Usually these describe the required performance of the system, although it is not uncommon to have requirements for the size of the object code (which may determine the number of integrated circuit chips required in an embedded system application) or the capacity of the system (such as in large information systems).

Computer programmers who are not software engineers often try to express requirements (either explicit or implicit) with phrases like "the program must be efficient," or "the program should be as fast as possible," or "the program must be memory-efficient." Because these requirements are not quantified, and probably not quantifiable, they are neither meaningful nor acceptable to a software engineer. The ability to measure offers the engineer a way to state requirements quantitatively, and then to demonstrate compliance with those requirements.

Discussion Question 8

How can we as software engineers rephrase these requirements in quantifiable—and therefore potentially measurable—terms?

3. To track progress and predict results of an engineering project

In a large engineering project, periodic measurement of what has been accomplished or completed allows the project manager to track progress quantitatively. These measures can be especially useful in the identification of unusual trends, so the manager can foresee problems and try to solve them before they get out of hand. This can include not only technical problems, but also schedule or cost overruns.

Discussion Question 9

Have you had to write a term paper or a major computer program and discovered the night before it was due that you still had 50% or 80% of the work ahead of you? Assuming that the problem was not just procrastination, how might you have been helped by a realistic schedule backed up by quantitative progress measurements?

In many kinds of engineering projects, including software engineering, products undergo a period of testing and tuning before delivery. Measurements of product defects, breakdowns, or successful performance can be made over time, and then trends can be analyzed. Software engineers, for example, use defect counts during testing to calibrate reliability models, which in turn can predict when system testing will be complete and the desired level of system reliability achieved.

4. To analyze costs and benefits

Here we are getting at the heart of engineering: making tradeoffs. There are almost always many ways to design engineered products and many ways to design the components and subcomponents of those products. Each design offers advantages and disadvantages, and the engineer must trade one quality against another. Sometimes we are willing to accept more of a negative quality in order to get more of another, positive quality; sometimes we accept less of a desirable attribute in order to get more of another desirable attribute.

If we are automotive engineers, for example, we must make tradeoffs among weight, fuel economy, passenger room, ride comfort, and price. Will we accept more weight, and therefore decreased fuel economy, to gain more room or more ride comfort? Will we accept a higher showroom price to gain improved ride comfort? Will we accept the cost in time and money of research to develop a more fuel-efficient engine or a computer-controlled dynamic suspension system if it means we can provide both more comfort and better fuel economy?

To answer questions like these, engineers must have quantitative data on the costs and benefits of each design. That data comes from measurement.

Discussion Question 10

The classic tradeoff in programming is *time* vs. *space*. What does this mean? What are some examples? Can you describe a situation from your own experience in which you consciously made a time/space tradeoff?

5. How Engineers Measure

Traditional engineering measurement is performed with *instruments*. Much of the progress in science and engineering over the past few centuries has been facilitated by the development of new and better measuring instruments. But what makes an instrument *good*? Two very important considerations are accuracy and precision.

The *accuracy* of an instrument is an indication of how much the instrument's reading differs from a known input. Accuracy is usually expressed either as a percentage of the maximum measurable value, or as a range of deviation from a correct value. For example, if a voltmeter that can measure up to 1000 volts is said to be accurate to 1%, we know that any reading is no more than 10 volts (1% of 1000) high or low. We could also say that the voltmeter is accurate ±10 volts (the symbol ± is pronounced "plus or minus").

The *precision* of an instrument is an indication of the repeatability of a measurement within a given accuracy. Suppose you measured a 120-volt source each day for a week with two different voltmeters, and you recorded these readings:

Day	Meter A	Meter B
Monday	125	120
Tuesday	126	117
Wednesday	125	123
Thursday	124	121
Friday	125	119

Meter A gave readings of 125 ±1 volts, while meter B gave readings of 120 ±3 volts. Meter A has better precision: ±1 volt is better than ±3 volts. However, we would also conclude that meter B is more accurate; it was never more than 3 volts off the correct value, while meter A was always 4 to 6 volts off the correct value.

An electrical engineer would also recognize that meter A could be *calibrated* so that its readings would have been 120 ±1 volts, making it both more accurate and more precise than meter 2. Calibrating a voltmeter may be as simple as adjusting the value of an electrical component (such as a variable resistor) in the instrument. In general, calibration of an instrument can improve its accuracy, but only up to the precision of the instrument. Meter B is probably already calibrated as well as it can be.

A calibration error is an example of a *systematic* error in measurement. These errors are a result of the physical limitations of instruments, and they occur in many forms. *Null-point* errors are caused when the zero or null reading on an instrument is improperly set, causing a constant shift in all readings. *Hysteresis* errors occur when a reading is influenced by the previous reading of the instrument, such as a voltmeter that gives a low reading when the needle approaches the correct value from below and a high reading when it approaches from above. *Parallax* errors occur when the measurements differ depending on the angle from the instrument to your eye.

Engineers are also concerned with *random* errors in measurement, which occur in the act of measurement itself, regardless of the systematic errors inherent in the instrument. Meaningful measurements are usually expressed not as a single value, but as a range in which the actual measurement lies (as in the example above, where the voltage measurement was 125±1). This range is the *absolute* error in the measurement. The *relative* error is the absolute error divided by the measured value; it is usually expressed as a percentage.

Reducing systematic errors in measurement may require better instruments or better calibration of instruments. Random errors can be reduced by making several measurements and computing an average. A more precise study of random errors and their reduction depends on a good knowledge of statistics, so we won't pursue that here.

Discussion Question 11

What are some common instruments that you use to measure the following quantities? Estimate the accuracy and precision of the instruments. What kinds of errors are common in these measurements?

Your height
Your weight
Your car's speed
The distance you drive your car on a trip
The pressure in your car's tires
A spark plug gap
The time it takes an athlete to run 100 meters
The temperature of a beef roast
The frequency of the middle C note on a piano
The thickness of a piece of paper

Discussion Question 12

What measurement instruments do you use that you consciously calibrate from time to time? Can you think of an everyday measurement where a null-point systematic error might be introduced purposely? Have you ever experienced a parallax error while you (or your passenger) were reading your car's speedometer or other instrument? Did the speedometer appear to read higher or lower to the passenger? How does this depend on whether the needle is in front of the numbered scale or behind it?

Research Question 13

What is a *vernier* and how does it work? What is its intended effect on the accuracy or precision of a measurement?

Engineers (and scientists) often use another measurement technique: *sampling*. This may be defined as selecting and measuring a representative part of a population for the purpose of deducing parameters or characteristics of the whole population. It is used in situations where it is impossible or impractical to measure the whole population.

Discussion Question 14

A little-known fact is that there are 51,500,000 hairs on the average horse. Suggest a sampling technique that might have been used to discover this fact.

Discussion Question 15

Suppose you are the manager of an engineering project with 200 staff members. You want to measure how much staff time will be spent on meetings, administrative paperwork, library research, laboratory work, writing reports, and work at the computer over the next year. Suggest a sampling technique that might provide estimates of these numbers without waiting the whole year.

A related kind of engineering sampling is seen in *quality control* in the manufacturing process. At the factory assembly line, we may take every 100th or 1,000th product for testing and measurement. Using a variety of statistical techniques, we draw conclusions about the quality of all the products from the measurements made on the sampled products. Then we adjust the manufacturing process accordingly.

As was the case with measurement error, a thorough discussion of sampling techniques depends on knowledge of statistics, so we will not pursue it here.

6. Concluding Comments

Measurement is an important tool for engineers. As a student of engineering, you should learn:

- what can be measured
- what should be measured
- what kinds of instruments are used in measurement
- why measurements are needed
- how measurements are used
- how to measure the important quantities in the branch of engineering you are studying

Learning to measure requires practice, so laboratories and other “hands-on” experiences are useful. But pay attention also to the measurements you make in everyday life—they can teach you a lot about measurement.

Large engineering projects require many kinds of measurements and generate an enormous amount of data. Professional engineers need a good background in statistics in order to use that measurement data effectively. You would be well served by including a statistics course in your studies.