Reflections on **measurement**


CEA

Étienne Klein

Quantified observation of the regularities occurring in reality is the very basis of science. In its principles, as well as throughout its development, science thus expressly bases itself on measurement. This is related to the very nature of the scientific project: for the investigation of a phenomenon to lie within the ambit of science, that phenomenon must be amenable to quantification, in a manner that is repeatable, and sufficiently precise, so that it may be associated to a quantity. In other words, it must be "measurable."
In common parlance, the term "measurement" refers to the operation that consists in recording, by means of a suitable device, the value of this or that physical quantity, for a given system. In more general terms, to measure is to compare, by means of a measuring instrument, the value of a quantity A in the physical world to a reference quantity A_0, taken as unit, and assumed to remain stable over time; and to express that comparison through the value A/A_0, this being the reading yielded by the measurement. This further involves providing an estimate of the quality of that operation, by specifying the uncertainty, or the margin of error, associated to it.

An opening onto the mathematization of the world

The prime virtue of measuring is that it makes us rise above the qualitative perception of things. In so doing, measurement opens up the possibility of the mathematization of reality: starting from a "datum" that is, at first blush, complex, confusing, even in some cases elusive, it maps it onto a numerical grid, enabling its quantification. It thus translates a "piece of reality" into a register having the ability to condense, sum up, characterize that item.
To measure a property of an object is, ultimately, to abstract this property, away from its material substrate, to relocate it in another place, in the form of a number, a curve, a formula. As the outcome of this projection into the world of numbers and digits, what is obtained is an – ostensibly "leaner" – image of the measured item.
And yet, measurement may not be brought down to a mere numerical tally: in the latter case, all that is involved is "counting", as e.g. the various constituent parts of an object. Measurement differs from this, in that it invariably entails an apparatus, together with a method, having the capability of extricating the measured entity, from its closed, or nonperceptible state. It has to set up a contact, mediate between the two quite distinct realities, that of the measuring instrument, on the one hand, and that of the thing being measured, on the other. If one is to "give good measure," a twosome needs must be involved, and the two must be able to interact. It will thus be seen that measurement has to do with conjugality: a thermometer does not measure its own temperature.
Nor should measurement be confused with some kind of quantitative language. On the one hand, this is due to the fact that, contrary to words, measurement is concerned with the universal, and is not dependent on a vocabulary: scientists are agreed both as to the operational units to be used, and the procedures to be implemented, so that findings, made accessible to all, may be open to comparison, and discussion. And, on the other hand, because the numbers that characterize the reading yielded by a measurement tell us much more about the object than do words, in language. To be sure, a body's temperature may be said to be scalding, or tepid, or warm, however such qualifications, on the one hand, are vague, and, on the other, are often distorted by the way they remain inextricably bound up with our sensory impressions: the personal relationship we entertain with the thing we seek to apprehend systematically confuses the operation. Surreptitiously, we substitute for that thing our own reaction to it, thus bringing in one further operator, namely our organism, and what it is accustomed to. Measurement, on the other hand, is intended to enable a reading to be obtained that is more certain, more objective, and more succinct.

> *"One should reflect prior to measuring, rather than measure prior to reflecting"*
>
> **Gaston Bachelard**
> *The formation of the scientific mind*

An ideal of objectivity

It has long been held against measurement, however, that, through the device used to carry it out, the observer, unwittingly, might bear on what is measured, interact with what he purports to capture, and thus modify it. The

argument, unquestionably, is valid, however it does not give its fair due to the "art of measurement," which consists, precisely, in ensuring such modification is, if not down to nil, at any rate kept to a minimum.
The example of the thermometer – a common, mercury thermometer, for argument's sake – serving to measure the temperature of water held in a vessel is illuminating, in this respect: to act as a thermometer (and thus to measure temperature while not altering it), the mass of mercury exchanging heat with the water must exhibit a heat capacity markedly smaller than that of the mass of water; in such conditions, the same amount of heat, passing from the water to the thermometer (or vice-versa), causes but little change in the water's initial temperature, even as it causes that of the thermometer to vary. The measured temperature may then be deemed to be the temperature of the water, to a very close approximation, since the measuring instrument has caused practically no disturbance to the system (the water) on which the measurement was being carried out. Just as in this model, provided by the thermometer, any measurement worthy of the name aims for a kind of perfect neutrality, with regard to what it seeks to capture: it relies on the implicit assumption that the measuring instrument it will be using is far more sensitive than the object being measured. Hence the commonly entertained notion that a measurement, of whatever kind, records something that exists "out there," while not modifying its properties; and that, consequently, its relationship with reality is a purely passive one. Ideally, it might even restrict itself to effecting a mere transfer, a carbon copy of reality, and have the ability, ultimately, to abolish all and any separation between measurer and measured, thus affording the occasion of an actual "contact" with reality, of a true apprehension of the physical world, as it subsists *in se*.(1)

Between theory and experience

No measurement may be interpreted without a model, or a theory of the phenomenon being measured. Which is why the concept of measurement lies betwixt theory and experience. It stands as a junction between them, even as it feeds into the dialectic that binds them together.
Any measurement becomes an integral part of the description of the phenomenon it has allowed to be quantified, a description which alone can make that measurement "mean something." As Franck Jedrzewski points out, "while determining a fact entails measuring it, it should also be noted that the measurement process does not boil down to determining a number, rather it invariably involves a law, or a postulate, as its underlying precondition. Measuring a force by means of a force gage assumes force is proportional to spring elongation. Determination of a temperature relies on the assumption the height of mercury is proportional to temperature variations."(2)
Hence, what a measurement reveals may depend on the theory that is looked to, in order to interpret it. For example, measurement of the position (as given by two angles) of a distant galaxy may be interpreted by assuming space is Euclidean (i.e., assuming a flat space, with no curvature), or by allowing for local spacetime curvatures, as provided for in general relativity theory: the position assigned to the galaxy will not be identical, for both cases.

Can numbers express the world, and contain it?

Measurement, of whatever kind, and whatever object it is applied to, invariably yields numbers. In the process, does it not relinquish the very essence of what it purports to express? Does it not withhold from us the thing it claims to encompass, in dismissing its spatiality and shape, to gain a few figures? How may one expect such a bare equivalent as a number to carry with itself, as though ensnared in it, something of the substance that gave rise to it?
Oddly enough, many a philosopher of the Enlightenment, from Montesquieu to Benjamin Constant through Rousseau or René de Chateaubriand, rose against the "folly of numbers" that might result from the extension, or generalization of measurement. These sundry thinkers implied that all measurement deceives us, by concealing from us the true inner content of things, or inflicting on it some irretrievable dissipation: in making identical, in some respects, realities that are truly incomparable, measurement was deemed to result in actuality being volatilized, leaving us to grasp but the ashes of numbers. Closer to us, Henri Bergson, in his *Essay on the immediate data of consciousness*, took up some of these arguments, expressing in turn a critique of the rising sway of quantification: while measurement is indeed a form of knowledge, he averred, it does not allow a "coming into coincidence" with the object measured, nor even any "overlap" with it; measurement actually draws us away from it, even as it endeavors to assist in its visibility, or intelligibility. According to Bergson, there is indeed but one path that allows entry into a thing, and that is by coming into coincidence, or entering into "sympathy" with its very evolution, thus unshackling it from the purported "hold" of numbers: a thing is a thing, nothing is equal to it, or indemnifies for it, and we have forfeited it whenever we grasp it through what it itself is not.

(1) Three quarters of a century ago, quantum physics brought about an upheaval in this classical concept of measurement: in this context, the measuring instrument unavoidably interacts with the object on which one seeks to carry out a measurement. That reappraisal forced physicists to address "the measurement problem in quantum physics," which will not be discussed here.

(2) Franck Jedrzejewski, *Histoire universelle de la mesure*, Paris, Ellipses, 2004, p. 10.

Laurent Guiraud/CERN

The preparations for the ATRAP experiment, investigating antihydrogen, at CERN in 2000, involving as it did highly sophisticated measurements, required for its implementation the use of some altogether traditional measuring instruments, such as this force gage.

That Bergsonian critique of measurement had one attractive aspect, in that it promoted a "conscious, deliberate return to the givens of intuition," however it remained oblivious of one essential point: measurement, while apparently depleting what it expresses, equally replenishes our understanding of it; though it takes in but a fragment of the world, yet it amplifies what it operates on.

Such is the paradoxical side of measurement: it allows a great deal to be gained, even though, through its offices, our grasp would appear to be diminished, or depleted. Paul Valéry very aptly expressed the fruitfulness of that contradiction, and the fascination it held for him: "I confess I have no idea how quantitative relations, obtained through measurements carried out from the outside on things, can, in so many cases, and to such remarkable approximations, yield predictions and allow verifiable applications. This irresistibly brings to mind a metaphysics of quantity. It is an extraordinary, paradoxical thing that science, based as it is on metrics and numbers, should have achieved such results that abstraction, in other words depriving things from most of their characters, combined with itself, should have yielded so many things, and so much power over things."(3)

The facts, indeed, stand: measurement does not diminish reality, it augments it. Far from crushing reality, it fosters its unfolding, by opening up the way to knowledge.

On the way to new phenomenalities

In the course of the history of science, measurement expanded along two directions. On the one hand, it gradually concerned itself with quantities that were ever less perceptible to the senses: velocity, familiar to us only through the speedometers in automobiles, is a quantity which is more abstract than length; acceleration is yet more abstract than velocity; magnetic field strength, electric charge are still less directly accessible; and what is one to say of particle spin? And, on the other hand, measurement gradually turned away from commonplace, macroscopic (human-scale) phenomena, to take on all manner of "extremes:" the ultramicroscopic, the very large, the extremely brief, the very distant, the unbelievably scarce, the very hot, the highly elusive… In every one of these new domains in the world, it has allowed regions of "phenomenality" to be conquered that had hitherto remained concealed, or inaccessible.

As may well be imagined, such extreme measurements are only achievable through the unfolding of a multiplicity of mediations, between the phenomenon itself, and its numerical capture – mediations that may be very indirect, or highly sophisticated: to measure the distance between the Earth and a galaxy, one may no longer rely on the act of placing a unit rod end to end; to evaluate a length measured in fractions of a micron, the good old sliding-caliper gage ceases to be of much use; as for watches, even when featuring a seconds hand, they have neither the ability to show the very short lifetime of unstable particles, nor the ages of stars, or the Universe. In each of these cases, as will be seen from what follows, other techniques must be brought in, and novel operational stratagems have to be devised, having the capability to capture as yet unknown aspects of reality.

> **Étienne Klein**
Physical Sciences Division
CEA Saclay Center

(3) Paul Valéry, *Cahiers (Notebooks)*, Paris, N.R.F., 1974, vol. II, p. 920.