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Speaking with Numbers: Scientific Literacy and Public Understanding of Science

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Abstract
Public understanding of science and scientific literacy is discussed. Scientific method, scientific process and scientific filter are reviewed accordingly. Basic terms of measurement and numerical calculation are outlined. Finally, fundamental requirements of scientific literacy and critical response skills are presented.

1. Introduction: Speaking with numbers

We use phrases like "It will probably rain this afternoon", "Istanbul is in high earthquake risk", "Our team's chance is very high in this game" everyday, and there is nothing unusual to use "high risk", or "low probability", etc. But, what if somebody says, for example,

- the probability of having rain this afternoon is 65 %, or,
- an occurrence of an earthquake with a strength of 7 or higher in this region in the next thirty years is 83 %, or,
- our team's chance in this game is 52 %?

What if the probability of rain is 55 %, or the risk of occurrence of the earthquake is said to be 45 %? Isn't it going to rain, or won't there be an earthquake in the next 30 years? What does it mean when one speaks with numbers? What do the numbers mean? How many of us realize the true meanings of the numbers we pronounce everyday?

Speaking with numbers means computations/calculations; making calculations/ computations means (mathematical or not) using a specific model; and using a model means many assumptions, approximations, statements, general rules (relations), etc. Perception, understanding, and evaluation of the meanings of the numbers we pronounce in a society necessitate scientific literacy.

2. Why Scientific Literacy Education?

Nobody would deny today that the achievements of science (and technology) have changed our lives. Consider the transformation of domestic life that technology has produced, the progress of modern medicine, the state of wireless communication, and the green revolution in food production. How can we explain the curious contradiction in the public attitude to science and the combination of respect and indifference? The discrepancy that accounts for the confusion in public opinion about science may be the power of science, combined with ignorance of the nature of science and suspicion about its claims and motives.

Scientific literacy is essential in a society because any conversation, speech, TV/radio news, public announcement possesses –more or less– scientific and technological content. Its perception, understanding and evaluation by the *man on the street* necessitates accumulation of useful information called *knowledge*, and, this is possible only and only if he/she is equipped with fundamentals of *scientific literacy*. This may be achieved during the primary/compulsory education by including, within the framework of *health and environment* (physics, chemistry and biology), the topics like energy sources and conversion, electromagnetics, light and sound, radioactivity, Earth and Universe, materials, etc. Also the average person should be well equipped with *data acquisition*, *correlation/cause/effect*, *models*, *epidemiology (statistical data acquisition and evaluation studies with large populations)*, *risk management*, *information-based decision making*, *uncertainty* and most importantly *bounds of science*.

Without scientific literacy it is hardly possible to understand why, for example, Norway, US and Russian Federation occupy first, seventh, and fifty-seventh positions in 2004, respectively, according to human development index (HDI) prepared by the United Nations Development Program (UNDP) [1]. He/she can not realize that this list is based on a model where statistics from life expectancy to education, infant mortality to gross domestic product, etc., are used as significant data.

Without scientific literacy the average man can not understand why World Health Organization (WHO) publishes a 60-page booklet on *establishing a dialog on risks from electromagnetic (EM) fields* [2], or why International Committee on Non-ionizing Radiation Protection (ICNIRP) is in need of announcing *a statement on general approach to protection against non-ionizing radiation* [3], together with public announcements. I personally have exercised communication difficulties about possible adverse health effects of EM fields while lecturing in public meetings. In a public lecture I remember, some have accused me of speaking on behalf of GSM companies while some others have thanked me for standing against them. In fact, I have only aimed to inform people about latest situation without making any comment.

Similarly, without scientific literacy the man on the street can not understand, for example, why WHO categorizes agents into four different carcinogenic stages – (1) *carcinogenic*, (2) *probably carcinogenic*, (3) *possibly carcinogenic* and (4) *unknown*. That's why we have seen news all around the world like "*According to WHO using mobile phones is equivalent to drink coffee*" reported by a reporter, who learns that extremely low frequency (ELF) magnetic fields and caffeine are in WHO's *possibly carcinogenic* list (WHO, according to all available evidence, has recently classified *ELF magnetic fields* as *possibly carcinogenic to humans*. Another agent also classified by the WHO in this category is *coffee*, which may increase *kidney cancer*; while at the same time may be protective against *bowel cancer* [2]).

Without scientific literacy it is difficult distinguish between a *scientific explanation* or an *absurd statement* when somebody on a TV or radio, is talking about a futuristic *prediction*. The average man can not distinguish between an *expert* or a *media clown*.

3. Science and Scientific Process

Science is important, nobody would argue on that anymore. Using the word *scientific* in front of a word/phrase as a prefix, like scientific agriculture, scientific investigation, scientific result, etc., is an attempt to get credit from the word science [4]. What makes science currently more credible than anything else? What is the difference/similarity between a research and scientific research, a method and scientific method, a result and scientific result, an answer and scientific answer, etc.? Why is it scientific to speculate about ozone gap in the atmosphere, but not scientific to predict what will happen next year by looking at playing cards, etc.?

The dictionary Britannica defines science as "*The study through observation and experimentation of the structure and behavior of the physical and natural world and society including a particular area of this such as the science of engineering, medical science, computer science, etc.*". How compact, complete and useful this definition is questionable and debatable, but one thing that can not be deniable about science is its special significance in the society, because of its achievements on changing our lives in the past century.

A flowchart of scientific process is pictured in Figure 1. Related to the physical and natural world including society, everything starts with a clear definition of a *problem*, no matter how and where it comes from (questions, curiosity, imagination, stupid ideas, previous knowledge, chance, etc.) and it ends up with general solutions as laws [5]. Scientific process deals with studies towards building models to simulate, test and predict behaviors under different parameters, and to estimate future events. Within the historical progress there have been, in general, three different solution approaches; religious approach, philosophical approach and the scientific approach. From the third century BC, to the seventeenth and eighteenth centuries science had been imprisoned in religious and philosophical approaches due to initial efforts of Plato and his student Aristotle. Scientific evolution reached a climax in the XVII and XVIII centuries, when science freed itself and became independent first with Galileo, Newton, Bernoullie, Faraday, and then Enstein, Feynman and many others (the aim here is not to discuss and/or criticize religious and philosophical approaches as they are related to beliefs and thoughts, and not the subject of this paper).

In fact, *science* is not an activity but a product of a human activity called *research*, just like the other commonly used word *technology*, which is the product of another human activity called *development*. The two words, science and technology (S& T), and other two, research and development (R& D) often go together and are sometimes used interchangeably; the word science is used to mean *knowledge* but sometimes it refers to the human activity itself, which is *research*. Development is commonly associated with engineering and technology, and generally problem solving. The word research is often prefixed nowadays with words like *pure*, *basic*, *applied*, *directed*, *military* or *civil*, *government-funded*, etc., [6].

4. Scientific Approach and Scientific Filter

Science / scientific study / scientific process starts with the definition of the problem, progress with independent, unbiased observations, perceptions, statements, intensive experiments and tests, and finally it reaches general solutions, after a long period of falsifications, tides, and it is rephrased within these steps. In this process, first the nonsense and errors, then fraud are eliminated. Obstacles and inadequacies are also discovered during this period. The socialization of the problem and the scientific progress is achieved first by public debate, and research proposals, followed by meetings, congress and symposium papers and journal articles, and finally by tutorials, textbooks and books, in a process which is called *scientific filter* (see Figure 2).

After this process and filtration the solution of a well-defined problem is publicized as a scientific law with its accuracy, resolution and range of validity. Falsification or failure of a law in explaining new phenomena in scientific progress is a serious crisis in science, often results in a revolutionary change and may cause totally re-phrasing (or re-definition) of the problem. Principles, like *objectivity*, *systematicity*, *reliability*, *repeatability*, *comprehensiveness* and the *precision* are the fundamentals of "*scientific approach*" (see Table 1).

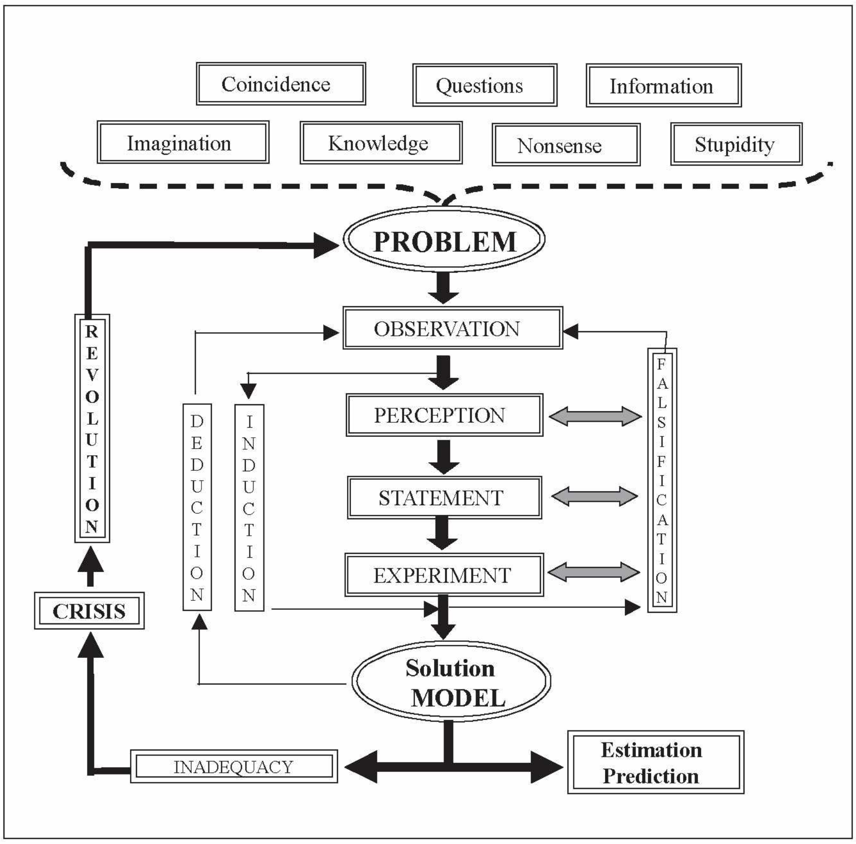

Figure 1. A flow-chart of the scientific process [4]

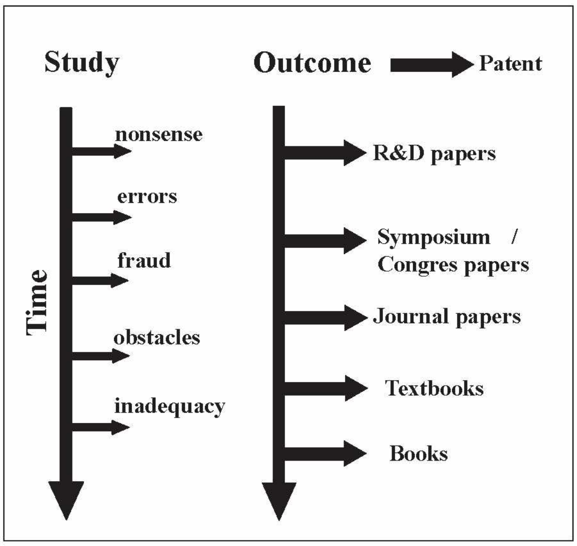

Figure 2. Scientific study, outcome and scientific filter

Table 1. Universal criteria for scientific process

Objectivity	Run always after the truth
Sistematicity	Always remember the cause and effect relation
Reliability	Similar methods should yield similar results
Repeatability	Different people should reach similar results
Accuracy	Certainty (bounds) of uncertainty should be clear
Modeling	Anybody who follows similar procedure can do it
Predictive power	Predictions towards future (extrapolation) should be possible

It should be noted that the degree of precision and predictive power achieved is only a question of research technique. The fact that social scientists, economists, or geophysicists have not developed their models that are as precise and predictive as physical sciences, does not necessarily mean that Social and Earth sciences are less scientific, but merely refers to the requirement of the development of "*better*" or "*more realistic*" models.

5. Measurement and Numerical Calculation

Speaking with numbers necessitates a good understanding of fundamental concepts of a measurement and/or a numerical calculation [7,8]. Concepts, such as uncertainty, accuracy (the ability of an instrument to measure true value within stated error specifications), precision (the ability to repeat measurements) and resolution (the smallest change in value that an instrument can detect) should be well-understood (I've seen engineers who present their results with, for example, 12-digits while numerical error limits it to, for example, 8-digits, and, while only 2-digit is meaningful because of the approximations made there).

- *Accuracy* is the closeness of agreement between a measured/computed value and a true value. Measurement accuracy is the ability of an instrument to measure the true value to within some stated error specifications. Numerical accuracy is the degree to which the numerical solution to the approximate physical problem approximates the exact solution to the approximate physical problem.
- *Precision* is defined as the variation of a variable's values obtained by repeated measurements.
- *Sensitivity* is the ratio between a small change in electrical signal to a small change in physical signal.
- Resolution is the smallest physically indicated division that an instrument displays or is marked, such as range resolution, picture resolution, instrument resolution, sensor resolution, camera resolution, etc.
- Uncertainty is the effects (error) of approximations, assumptions on the result.

The error in a measurement and/or numerical calculation is basically divided into two: systematic and random. *Systematic errors* involve the comparison with a true value, which determine the accuracy of the measurement and/or numerical computation. On the other hand, *random errors* are related to the scatter in the data obtained under fixed conditions which determine the repeatability (precision) of the measurement.

Systematic errors can be minimized through careful calibration, whereas random errors can be reduced by repeated measurements and careful control of environmental conditions. An ideal measurement instrument is highly accurate with high precision. High precision alone does not imply minimal error. For example, an experiment could hide systematic errors and yet highly repeatable (precise) measurements could be performed, thereby always yielding approximately the same, yet, inaccurate values.

The terms uncertainty and error have different meanings in modeling and simulation. Modeling uncertainty is defined as the potential deficiency due to a lack of information. On the other hand, modeling error is the recognizable deficiency not due to a lack of information. Measurement error is the difference between the measured and true values, while measurement uncertainty is an estimate of the error in a measurement. Modeling and simulation uncertainties occur during the phases of conceptual modeling of the physical system, mathematical modeling of the conceptual model, discretization and computer modeling of the mathematical model, computer modeling of the discrete model, and numerical solution. Numerical uncertainties occur as a result of discretization, round-off, non-convergence, artificial dissipations, etc.

A measurement/ calculation result "a" should be given as ($a \pm \Delta a$), which means that the value may be anything between $a-\Delta a$ and $a+\Delta a$. Here, "a" is the result, "Δa" is the absolute error, and "$\Delta a/a$" is the relative error. For example, if the measured speed is 98 ± 3 km/hr, then the real value may be anything between 95 and 101 km/hr. The total error is the sum of individual errors for the arithmetic combination of two measurements. The total relative error is the sum of individual relative errors for the multiplicative combination of two measurements.

Understanding the true reading of a measurement device is also important. For example, if the accuracy of a digital multimeter is given as ±(0.25 % reading + 2 digit), then, the user should multiply the value he/she reads from the multimeter by 0.25 % (or, 0.0025), (called scaling error); add two times the value of least significant digit in the reading (called quantization error); and then records the result. Here is an example: What is the total error if the measured value 15.00 V with a 20 V scale of a digital multimeter given as ±(0.25 % reading + 2 digit)? The answer is: Scaling error: $0.0025 \times 15.00 = 0.0375$ V, Quant. Error: $2 \times 0.01 = 0.02$ V, Total error: $\pm\ 0.0375 + 0.02 = \pm\ 0.0575$ V.

Critical response skills

How does the average man distinguish between worthless statements, ideas, beliefs and scientific speech or explanations? The answer is to equip himself with critical response skills [9]:

- Do have information before reaching a decision and having an idea, or joining discussions (*Feynman pointed out in his Nobel Bestowal Ceremony that people speak about and discuss on subjects that nobody knows a thing [10]; they speak about, for example, weather, social problems, economy, etc., but don't speak about physics because somebody knows something about it*).
- Clearly indicate all assumptions of your statements and claims.
- The results should logically be obtained from the evidence you present (*the truth in the statement "most rich people own automobiles" does not prove that the opposite "the people who own automobiles are rich" is true*).
- Choose the right thing when you make a comparison (*look at the comparison "being a champion is like cheating on your girl friend, imagine the excitement!"*).
- Do not confuse the truth with ideas/hypothesis/assumptions; don't let your ideas make you blind.
- Do not authorize (give credit) fame, listen to the expert (*remember how effective it is for the people who watch a famous model, or a TV reporter loosing weight with a kind of a diet, as compared to listening to a dietician*).

- Do not use indefinite/uncertain phrases like "*science tells us* ..." or "*famous doctors claim that* ...", etc.

Experts and researches should

- always remember that there is also a control group against the test group (*remember the statistical significance; which is about deciding whether differences observed between groups in experiments are "real" or they might well just be due to chance; the bigger the difference between groups the less likely it is that it's due to chance and the larger the groups the more likely it is that the observed difference is close to the actual difference*).
- not use graphs with peculiar or partial scales, or without scales.
- always mention the deviation around the mean or average (*think about the distribution of two groups of five people with the average age of 50, while the ages in the first group are 10, 25, 50, 75, 90; the others in the second group are 48, 49, 50, 51, and 52. Can their behaviors be the same if they are used as test groups?*).
- always mention the sample space when speaking about a statistical percentage or fraction (C*an you figure out which is worse when saying "50 % increase has been observed in carcinogenic incidents" when the number of total patients observed is 3 or 300?*).
- not confuse or compare absolute values against ratios or percentages (*Do you understand the difference if I say, for example, "the increase of street chasing in London compared to last year is ten percent, while there are 123 incidents in Berlin"*).
- not forget the intersection when using groups such as "young people", "white people", "consumers", etc.
- not present your results with insignificant / misleading) manner, because it adds to the accuracy, resolution, and precision of your data (*e.g., presenting a computation result with 12 digits, while numerical errors limits it to 8 digits, and while only 2 digits is meaningful because of the approximations made in the model.* T*ry to find out what is wrong with "presenting 189 patients out of 550-total as 34.36 % "*).
- not present your results/explanations as if they are the only ones or as if there are no others.

6. Conclusions and Discussions

The untraceable scientific advances, followed by fast changes in technology have revolutionized life styles in modern society, from the fields of communication to marketing, education to medicine, and so on. The society must be prepared accordingly, especially in terms of critical response skills. Novel education techniques such as *problem-based learning*, *inquiry-based teaching* may be discussed in detail to educate people for better scientific literacy. Subjects like *energy sources and conversion*, *electromagnetic radiation*, *thermodynamics*, *material science* – to some extend –should be covered during the k12 education (if not, in the university curricula). People should also be well-equipped to deal with *data acquisition*, *correlation*, *models*, *epidemiology*, *risk management*, *information-based decision making*, *uncertainty* and *bounds of science*. Finally, lectures like *Science Technology and Society*, or *Public Understanding of Science* should be included in all educational levels.

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