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THE LIMITS OF SCIENTIFIC KNOWLEDGE

MICHAEL J. MORAVCSIK

Institute of Theoretical Science, University of Oregon, Eugene, Oregon 97403, USA

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Summary

The article presents a phenomenological analysis of those factors which influence the amount of scientific knowledge a group or the whole human race can acquire in a given time period, or between now and the indefinite future. Some rather broad conclusions can be drawn from the results with respect to scientific research policy.

Introduction

With the rapid acquisition of scientific knowledge by the human race in the past few hundred years, the question naturally arises as to whether the total amount of scientific knowledge ever to be attained by humans is finite or not. I will try to analyze this question and touch upon some related ones: If this total knowledge is finite, what are the limiting factors? How does this finiteness affect human development? How does it affect the scientific and technological 'power balance' among nations? What implications does it have for the scientific and technological gap between 'advanced' and 'less developed' countries?

When embarking on such an ambitious task, some caution is advisable. The problem we are attacking is, in mathematical terms, highly non-linear, or, if you wish, it is a problem with a strong feed-back mechanism built into it. Not only that, as we will see, the various factors influencing the extent of acquirable scientific knowledge are themselves influenced by the extent of that knowledge, but also our perception of what the influencing factors are and what their time evolution will be depends on the future development of science. Considering these huge uncertainties in the formulation of the problem and in view of the well-known tendency of feed-back or self-consistent problems to be sometimes highly unstable under small variations in some of the components, no quantitative analysis will be attempted except in a sketchy fashion. It is possible, however, that one could follow up the present considerations, which define the significant factors, by a more thorough discussion of these factors, leading to a quantitative treatment of the extent of acquirable scientific knowledge, at least extrapolated to the not too distant future.

I will assume that the packing-down process of science will continue to operate about the same way as it has in the past. As science is discovered, first the new knowledge is comprehended in a redundant and disorganized way. As time goes on, however, our understanding of the new knowledge is simplified and clarified, and, as the irrelevant and peripheral drops away, a much more economical form of storage can be developed for the new piece of knowledge. If this were not the case, a human lifetime would not be sufficient even to acquire previously obtained knowledge in a given field, let alone to add to it, and so the acquisition of new scientific knowledge would stop. I will, therefore, have to assume in this analysis that such a packing-down of knowledge will continue at a sufficient rate so that the mastery of previously acquired knowledge will not become a limiting factor in the acquisition of new knowledge. Increased specialization also helps in this respect, but there might be a limit to the extent people can specialize in scientific areas.

Beside technical questions like the non-linear nature of the process, and the necessity to make assumptions about the compactability of scientific knowledge, there are other conceptual problems to face also. In particular, it might be objected that it is not possible to quantify knowledge, and even if it is, we lack reliable measures of such knowledge to carry out the task set in this paper.

There is an element of truth in such objections, but not enough to make the task completely impossible. First of all, there can be little doubt that scientific knowledge is cumulative. Even those who like to assert that at each "paradigm change" all previous knowledge is wiped out (a most dubious proposition in itself) must admit that, as indicated by a functional use of our understanding of nature in the form of control over our material circumstances and expansion of our domain of non-material aspirations, scientific knowledge has made gigantic progress in the last three centuries. At least in this sense, therefore, but most likely in a much broader sense also, scientific knowledge is cumulative in that new knowledge can and must be built on knowledge acquired in the past.

Such a concept of cumulativeness implies the existence of some sort of a quantitative indicator of the amount of scientific knowledge, however crude it may be, and regardless of whether we can, at the moment, define, articulate, and monitor such indicators so that they form a fairly rigorous measure.

Another way of relieving some of the doubts concerning whether the task set in this discussion is feasible or not is to differentiate among the various meanings the phrase "scientific knowledge" has. In particular there is a distinction between what one might call conceptual knowledge and pragmatic knowledge. The former would refer to the framework within which we offer an explanation of natural phenomena and in terms of which we justify the predictions we make concerning phenomena about to be observed. In contrast, pragmatic knowledge would simply denote the domain of phenomena which we can predict with a satisfactory degree of reliability and accuracy.

The task of measuring scientific knowledge is to be interpreted in terms of this second meaning of scientific knowledge, and it is in this sense that there is little doubt about the great progress made in the last centuries in science. The number and type of natural occurrences that we can satisfactorily predict in 1975 is certainly immensely larger than it was in 1675.

This sharpening of the definition of our task helps us to counter those who claim that science is unmeasurable since its history is merely a set of "paradigm-changes", which occur discontinuously, and hence the whole process lacks a quantitative character. While on a conceptual level science might conceivably be described in that fashion, the consequences of these paradigm changes in terms of our ability to predict phenomena vary in a much more continuous and cumulative way. For example, our "switching" from classical mechanics to quantum mechanics, from a pragmatic point of view, can simply be described in terms of the quantitative expansion of the domain of physical phenomena for which there is a satisfactorily simple and economic way to make reliable and accurate predictions.

In accepting this point of view, we also avoid having to make aesthetic value judgements about the superiority of one paradigm over another. For example, we do not have to decide whether we "believe" in quantum mechanics providing a fundamental explanation of microscopic phenomena, or whether a "hidden variables" type of explanation is and must be underlying it (in which case quantum mechanics should be considered only a phenomenology). There is no question that quantifying such disputes would be at the best a very difficult assignment. It is, therefore, reassuring that these problems need not be faced when talking about a possible quantification of scientific knowledge, as long as we define the latter in the pragmatic way, that is, in terms of the realm of phenomena that can be predictively dealt with.

Thus, in principle, the task is not impossible. The next question then is whether there is in fact a proper measure in existence now which can be used in the framework outlined in this paper. In deciding this we run into two separate problems.

The first pertains to the exact definition of the quantity we want to measure. In another article[1] I spoke of the three concepts of scientific activity, scientific productivity, and scientific progress. It is clear that, from the present point of view, we are interested in scientific progress only. If so, however, we must be sure that the measures we use pertain to this concept and not to scientific productivity, and certainly not to scientific activity.

This brings us to the second problem pertaining to measures. There are now quantitative measures used to gauge scientific output, such as the number of publishing scientists, the number of publications, the number of citations, etc. Not only are these measures, however, of debatable validity for internal reasons, but also none of them can be definitely claimed to pertain to scientific progress as opposed to activity or productivity.

And yet, the imperfection of existing measures should not discourage us from trying to make use of considerations like those in this article. Using the best measures available at any given time, and with full awareness of the uncertainties in the result due to the shortcomings of these measures, such considerations can give us at least some insight into the patterns of growth of scientific knowledge.

In particular, one could ascertain the consistency of the scheme by applying it to a period in the history of science, where the patterns are already a matter of record. In doing so, one might be faced with the task of establishing the values of the input parameters which are necessary in the formalism suggested in this paper, and this might in some cases be hard. But quantification in a brand new area is at first always a crude, rudimentary, and approximate undertaking. If the first results are sufficiently encouraging, refinements, rigor, and increase in operational effectiveness will undoubtedly follow.

The Constituents and Their Relationship

In order to facilitate the discussion, I will introduce symbols for the various factors that can influence the amount of scientific knowledge attainable by man. Each of these is a function of the time t.

$S(t)$, the total amount of scientific knowledge, whether attainable by human or not;
$P(t)$, the size of the human population;
$s(t)$, the fraction of the human population capable of pursuing science;
$G(t)$, the per capita annual gross world product;
$K(t)$, the amount of scientific knowledge attainable by one scientist per year;
$C(t)$, the cost of supporting one scientist per year;
$f(t)$, the percentage of the annual gross world product to be devoted to science;
$A(t)$, the amount of scientific knowledge acquired by the human race per year;
$Q(t)$, the number of scientists in existence;
$B(t)$, the amount of scientific knowledge acquired by the human race up to time t;
$m(t)$, the 'morale' or 'will' factor, the percentage of 'efficiency' with which the human race acturally pursues scientific resarch compared to that it would be capable of at that time due to other, material factors.

We have the relationship

$$\int_{-\infty}^{t} A(x)dx = B(t) \tag{1}$$

Furthermore, we have $Q(t) = P(t)s(t)$ in the case of 'manpower limitation', and $Q(t) = G(t)P(t)f(t)\,[C(t)]^{-1}$ in the case of 'resource limitation'.

Finally $A(t) = Q(t)K(t)m(t)$, provided that $B(t) < S(t)$. The schematic relationship among these quantities is given in Figure 1.

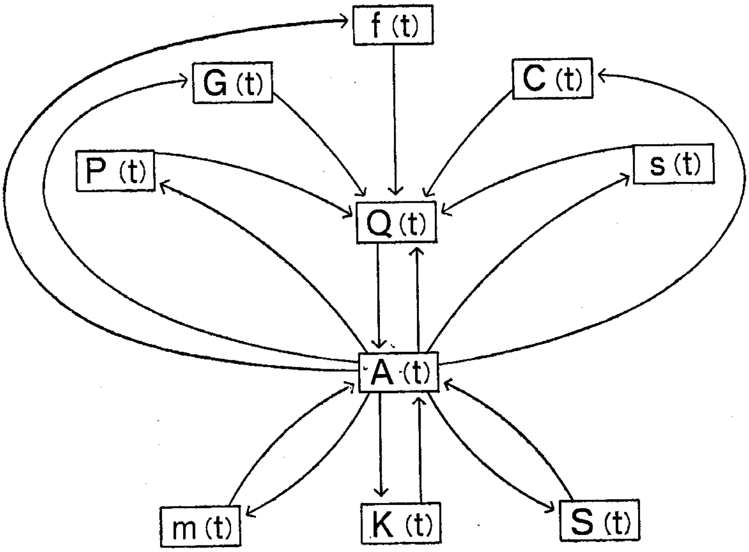

Fig. 1. Schematic relationship among factors influencing the extent of humanly attainable scientific knowledge. For the notation see text.

Analysis

I will now briefly discuss each of the quantities listed in the previous section.

S(t): Whether science itself is finite or not is a matter of conjecture. A number of times in the past a branch of science appeared to be completely uncovered in its basic principles, but each time this appearance turned out to be a mere illusion, when suddenly a new unexplored vista opened up[2]. Furthermore, even areas of science basically well understood provide new realms of discovery from time to time, as a result of interaction with other areas of science, or as a result of new technological developments. Laser optics serves as an example. And yet, some prominent contemporary scientists maintain that science (or at least a main branch of science) will soon be 'a closed subject'[3].

If S(t) is interpreted as the total amount of scientific knowledge *in principle* attainable by mankind, another constraint may come from the limitations imposed by the observer-object relationship. In quantum mechanics, for example, there are limits to what can be observed without altering the system, and some such constraints might also be present in biological or psychological self-observation.

In the above section S(t) was listed as a function of time, because one must allow for the possibility that the laws of nature themselves are in constant evolution and hence their extent is a function of time. Present evidence supports the contention that the known laws of nature have not changed significantly in the past, but not only is the evidence for this rather tenuous, but it also does not exclude the possibility that we have simply not discovered yet the 'growing edge' of natural laws.

The possibility that the total amount of scientific knowledge attainable by man is finite because the knowledge is finite is the most obvious one of the types of limitations we can have and hence this will not be discussed further.

P(t): Momentary considerations would suggest that the size of the human population must level off since the energy and meterial resources of the earth are finite. In a long-range study like the present one, however, it might be somewhat precipitous to accept this suggestion as a fact, since as long as the energy and material resources of the universe as a whole are infinite, one cannot exclude the possibility that future technology might be able to make use of them.

s(t): The fraction of the population capable of scientific research is certainly limited. It has been estimated[4] to be a few percent at the present. With eugenics the percentage might be increased in the future. However, it can obviously not be more than 100% and so s(t) (as well as the other percentage type factors like f(t) and m(t), all denoted by lower case (letters) cannot make A(t) or B(t) infinite by increasing from an already finite value to the maximum value of 100%. They can however, help to keep A(t) or B(t) finite by *decreasing* sufficiently fast with time. In contrast, the other factors, denoted by capital letters, do not have *a priori* upper bonds.

G(t): This quantity is particularly strongly coupled to the quantity of science at our disposal, since it is the technology growing out of science that allows G(t) to grow with time, which in turn is a crucial factor in determining the amount of scientific research that can be performed.

K(t): This quantity is a crucial one and is in turn dependent on several variables. First, it is possible that as scientific research reaches farther and farther away from our everyday experience, it will be increasingly harder for the human brain to comprehend new natural laws. This is partly because our 'intuition' might get weaker (since the origin of intuition is in experience), and partly because our brain, whose structure is determined by a limited assortment of natural laws pertaining to a very limited range of the basic variables (time, distance, energy, etc.), might find it harder to digest and order phenomena pertaining to other laws and other ranges of variables. On the other hand, two other prospective developments might counterbalance this retarding effect. If eugenics becomes a practical procedure, it could extend the capability of the human brain, though most likely not to an infinite extent. A much more likely possibility is artificial intelligence, that is, the use of advanced computers and artificial brains to do scientific research. The *number* of such brains appears to be limited only by the amount of raw material and energy available to us, which in turn might depend only on whether the universe is infinite or finite. Incidentally, the total amount of energy available to us also limits the total acquirable scientific knowledge in a different, more general way. Information theory tells us that the acquisition of knowledge runs counter to the second law of thermodynamics and hence requires energy. Thus, if the total energy supply of the universe is finite, the total amount of knowledge we can acquire must also be finite. This in turn raises the intriguing possibility that perhaps the total energy supply of the universe is insufficient to describe all the laws that govern it, a result that would undoubtedly be used by some to 'prove' the existence of God (i.e. a being that can transcend the second law of thermodynamics).

C(t): The cost of maintaining a research scientist has been increasing as we explore realms of nature farther and farther away from our natural environment representing the ranges of variables in which our body and direct senses operate, and therefore as we need more and more elaborate equipment to create to us unusual conditions and to convert the observations of these conditions to stimuli of our direct senses. It is hard to see how this increase in cost can be halted in the future.

f(t): This is again a percentage factor, and hence whether it is kept at 0.3% (as it is for basic scientific research in an average 'advanced' country), or is increased even to 100% makes little difference in the long run from the point of view of whether the amount of acquirable scientific knowledge is infinite or finite. On the other hand, if f(t) *decreases* with time sufficiently fast, it might have a profound effect on the amount of acquirable science.

Finally we come to

m(t): In a sense, this is a catch-all factor designed to stand for all the nonmaterial effects. It is, however, an extremely important factor. At the moment, for example, there are several trends in evidence that might threaten to make m(t) decrease with time: (a) 'Science is not relevant to present day problems'; (b) 'Science is bad because of the technology it produces'; (c) 'Technology is bad for the environment' (If technology stops, science will also come to a standstill, since continued scientific research depends on the availability of modern technology); (d) 'Growth, change, and progress are bad *per se*, and one should strive for a steady state human society'; (e) 'One should live to enjoy, and no work needs to be done beyond what is necessary to make a living.' This hedonistic outlook has contributed in the past to the stagnation and eventual downfall of particular civilizations, but in an increasingly closely knit, affluent, and tolerant world with extensive systems of financial security for everybody regardless of performance, stagnation might become a much more wide-spread phenomenon; (f) 'Science is morally bad because it contradicts a certain ideology'. There are a number of historical and modern examples for such an inhibiting effect on a relatively small scale. If a single ideology ever captures much of humanity and remains in control, this might become a dominant factor. (g) Science might drown in its own management. Constantly intensifying infighting and friction within the scientific community as well as an overly rapid increase in the scientist-hours spent on managing the machinery set up for the acquisition of new scientific knowledge might make m(t) a decreasing function of time.

Some Consequences

On the balance, where do we stand? Is the total amount of scientific knowledge ever attainable to mankind finite or infinite? Our analysis cannot give an unambiguous answer, but we see that the answer *could* be 'finite' if one or several of the following circumstances exist:

(a) Science itself is finite.
(b) The human population levels off.
(c) The human race deteriorates (or science gets difficult) so that an increasingly smaller percentage of humans is capable of pursuing scientific research.
(d) The per capita annual gross world product fails to grow.
(e) The amount of science a scientist can acquire per year decreases.
(f) The cost of supporting a scientist increases.
(g) The fraction of the total financial resources devoted to science decreases.
(h) The total energy supply of the universe is finite.
(i) The will of humanity to engage in scientific research decreases.

Most of these are not sufficient conditions by themselves, but their quantitative extents, together with those of other factors, will determine whether they result in finiteness or not.

To counterbalance these, there are other factors, to some extent under our control:

(a) From time to time throughout the coming centuries, a balance reassessment must be made as to, in view of the state of science and technology at that time, imposing an upper limit on the size of human population is warranted or not.

(b) Provisions should be made in human society that a non-decreasing fraction of the population continue to be in the position of pursuing scientific research. From the point of view of the present considerations, the exact size of this fraction is not crucial.

(c) The continued growth of the per capita gross annual world product is rather important to counterbalance the expected continued rise in the annual cost of research per scientist.

(d) Special attention must be paid to minimizing the amount of energy and money expended per unit amount of new information acquired.

(e) Eugenics, and particularly the efficient development of sophisticated artificial intelligence is likely to play a crucial role in determining the amount of acquirable scientific knowledge.

(f) Provisions should be made in human society that a non-decreasing fraction of the annual gross world product be devoted to scientific research.

(g) Since fear, emotionalism, and misinformation bring about low morale with respect to the human determination to pursue scientific research, both among scientists and among the human race as a whole, these tendencies must be recognized at an early stage when they occur and must be counteracted. The history of science has shown so far that such anti-science trends occur periodically, in fact almost constantly, each time wearing a slightly different garment. Even though so far science has always emerged the winner in the long run, this outcome cannot be taken as inevitable for future encounters.

These are qualitative conclusions. To utilize the quantitative aspects of the formalism in the above section one would need to know the input functions. Even if their values were known at the present, to calculate $B(\infty)$ or even $B(t)$ for some distant future time, one would need the form of these input functions also well into the future. This is clearly unfeasible at the present.

One can use the formalism, however, for two much more modest aims. First, one can construct models for the input functions and study their consequences, thus gaining some information for science policy decisions concerning manpower and resources to be devoted to science. Second, one can simply use the present empirical form of these functions (establish on the basis of the last one or two decades) and ascertain from their use the probable trend for $A(t)$ over the next few years.

The first of these uses will not be considered in this paper, mainly because there is a wide choice in the possible input functions one can use, and hence working with these just in the abstract, without considering a specific practical situation, appears to be too academic to be of interest in an article like the present one. I therefore turn now to the second use and make an estimate of A(t), using the present forms for P(t), G(t), K(t), C(t), f(t) and m(t).

For P(t) I will take an x% annual increase, for G(t) a y% annual increase, and for C(t) a z% annual increase. For the other three functions, K(t), f(t) and m(t), I will use, for the moment, constants. We then have

$$A(t) = \text{const. } \exp\left[\frac{(x+y-z)t}{100}\right] \tag{2}$$

Thus, whether the rate of acquisition of new scientific knowledge increases or decreases depends delicately on the balance of the above factors. Using some present values[5] for these factors, namely

$$x = 3 \qquad y = 5 \qquad z = 9$$

We find that $A(t) = \text{const. } e^{-0.01t}$, that is, the rate of acquiring scientific knowledge is decreasing. Slightly different values for the above parameters might, of course, give a slow increase instead of a slow decrease, but in any case it appears to be incorrect to maintain in the above described situation that we live in an age of "exploding" scientific knowledge.

Furthermore, small changes in the other factors so far assumed to be constant might have a decisive effect. For example, if m(t) decreased by w% a year, we would have

$$A(t) = \text{const. } \exp\left[\frac{(x+y-z-w)}{100}\,t\right] \tag{3}$$

and using $w = 3$ (a very small value indeed), we would almost definitely obtain the result that the rate of acquisition of scientific knowledge is decreasing.

Such a small change in the rather intangible m(t) would hardly be ascertainable in less than a decade or so, which makes such predictions the more difficult.

Of course, a decreasing A(t) even if continued indefinitely does not necessarily mean a finite $B(\infty)$. An A(t) decreasing in the fashion shown in this example, however, would lead to $B(\infty)$ being finite. Since my estimate of P(t), if extrapolated over several decades, will appear too large to many, and since m(t) and f(t), being functions bounded from above, cannot bring relief, the importance of increasing K(t) becomes quite evident from this example.

It might also be noted that in the above example the absolute number of scientists stays approximately constant, so that the scientists as a percentage of the total population decreases. Thus, even from that point of view, in the above model it is inappropriate to say that we live in an increasingly more and more scientific civilization.

Finally, I will turn to two questions related to our main problem under discussion.

First, assuming that the total amount of scientific knowledge acquirable by humans is finite, does it follow that technology is also similarly finite?

The answer appears to be both yes and no. It is likely that a finite set of laws of nature can be combined in an infinite number of ways to produce technological applications. But it also appears likely that such applications will become increasingly more inconsequential unless new scientific knowledge is injected in them. Thus, in the dynamic sense of the word, technology also stops if science does. This has significant implications since, as we have seen, science and technology are strongly linked through a feed-back mechanism[6]. If the acquisition of scientific knowledge slows down, the slow-down of technology will follow (perhaps with a time lag of a few decades), and this in turn will further slow down progress in scientific research.

The second interesting question related to our main topic is this: What is the implication of the extent of humanly acquirable scientific knowledge for the scientific and technological gap between more and less developed countries?

One might ask, of course, whether in the present very long range considerations it is not anachronistic to talk about more or less developed countries. It is possible that future social and political development will bring about a completely equalized and homogenized world society where countries do not exist and differences between groups of people are not tolerated. It is, however, at least equally likely (on general grounds of statistical dynamics) that some groupings of people will persist and that differences in the level of knowledge and achievement between such groups will also continue to exist. Thus the question of how these differences are affected by the extent of humanly attainable scientific knowledge is worth discussing.

It would appear that the answer to this question depends not only on whether the humanly acquirable scientific knowledge is finite or infinite but also, in case it is finite, whether the limit is reached suddenly or asymptotically.

If the humanly acquirable scientific knowledge is infinite, the balance between advanced and less advanced countries will be determined by the same factors as today, that is, the extent of this scientific knowledge will have no effect on the balance.

A similar situation will prevail if this acquirable knowledge is finite but the limit is reached asymptotically. As the acquisition of new scientific knowledge becomes more and more difficult (for any of the reasons outlined before), the relative balance between the advanced and less advanced groups, other things being equal, will not change.

One should, of course, emphasize the phrase 'other things being equal', since, then, just as now, 'advanced' groups might become 'less advanced' and vice versa. This can occur on account of any of the reasons inhibiting science if it affects preferentially one group compared to another[7].

If, on the other hand, the limit of acquirable scientific knowledge is reached relatively suddenly (e.g. because scientific knowledge itself is finite), the situation would appear to be drastically different. Again, other things being equal, such suddenly reached upper limit would give an opportunity to the 'less advanced' to catch up within a relatively short time, beyond which time parity could be maintained indefinitely.

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References

1. Moravcsik, M.J. (1973) Measures of Scientific Growth, *Research Policy* **2:3**, 256
2. The best known of these examples is the euphoria in physics at the end of the 19th century when classical electrodynamics was completed and the subsequent opening up of atomic, nuclear, and particle physics.
3. See for example Feynman, R. (1964) in his Messenger lectures, Cornell University.
4. See for example Derek de Solla Price (1963) *Little Science, Big Science*, pp. 50-54 Columbia University Press, New York.
5. I am indebted to Derek de Solla Price for helpful correspondence in connection with estimates of these figures,
6. It has been argued at times, using historical examples, that technology can develop also in the absence of the corresponding science, essentially by trial and error. In future technology, however based on natural laws not within our direct everyday experience, such an occurrence seems highly unlikely. Some consequences of a slow-down of technological progress have been analyzed in Hagen, E.E. (1972) Limits to Growth Reconsidered, *International Development Review*, XIV (2), 10.
7. See e.g. Moravcsik, M.J. (1973) A Chance to Close the Gap?, *Science and Culture* **39 (5)**, 205.

บทคัดย่อ

บทความนี้เสนอการวิเคราะห์เชิงปรากฏการณ์ เกี่ยวกับปัจจัยต่าง ๆ ซึ่งมีผลกระทบต่อความรู้ทางวิทยาศาสตร์ ที่มนุษย์กลุ่มหนึ่งหรือทั้งหมดสามารถหามาได้ ในช่วงเวลาที่กำหนดหรือไม่กำหนดในอนาคต จากนี้สามารถสรุปผลบางประการอย่างกว้าง ๆ เกี่ยวกับนโยบายวิจัยวิทยาศาสตร์ได้