How Many Scientists Does a Country Need?

S. George Philander
University of Cape Town, South Africa
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Education is a critical component of South Africa's efforts to alleviate poverty, the country's highest priority. For effective allocation of the limited resources available for education, it is important to identify and assess the different ways in which education can contribute. For example, what fraction of the resources should be allocated to the elimination of illiteracy, to primary, secondary and tertiary education, and to the establishment of centres of excellence devoted to research in certain scientific fields? Information relevant to this question is available on the next page in the form of graphs and tables. Fig.1 shows that the wealth of a nation is correlated with the citations earned by the publications of its scientists. In Table 1 it is evident that those scientists, with PhD's, are more numerous in rich than poor countries. The ranking of universities in Table 2, based mainly on the publication records of the staff, confirms that most of the highly cited scientists are at institutions in rich countries. The following inferences are sometimes drawn from the results in fig 1 and the tables.

(i) Scientists contribute directly to the wealth of a nation (by means of discoveries and patents). It then follows that, in poor countries, scientists should be encouraged to do more research, and to publish more papers. Furthermore, poor countries should increase significantly their number of Ph.D's (scientists who publish papers.)

These inferences may not be valid because correlations do not necessarily imply causality. The following inference can also be drawn from the results in fig.1:

(ii) Rich countries can afford to employ many scientists whose publications increase mainly the glory of the nation, especially when those papers appear in journals such as *Nature* and *Science* which receive enormous public attention. Poor countries where education levels are low can ill-afford the luxury of increasing the number of over-educated scientists, with PhD's, who write papers that are mostly of academic interest.

Other possibilities that fall between the extremes of (i) and (ii) include the following:

(iii) Scientists contribute to the wealth of a nation indirectly, by training exceptional students who create wealth by starting companies such as Microsoft, Google etc. The scientists can help attract those students to technical fields and to their institutions by writing papers that get attention (that are cited frequently.)

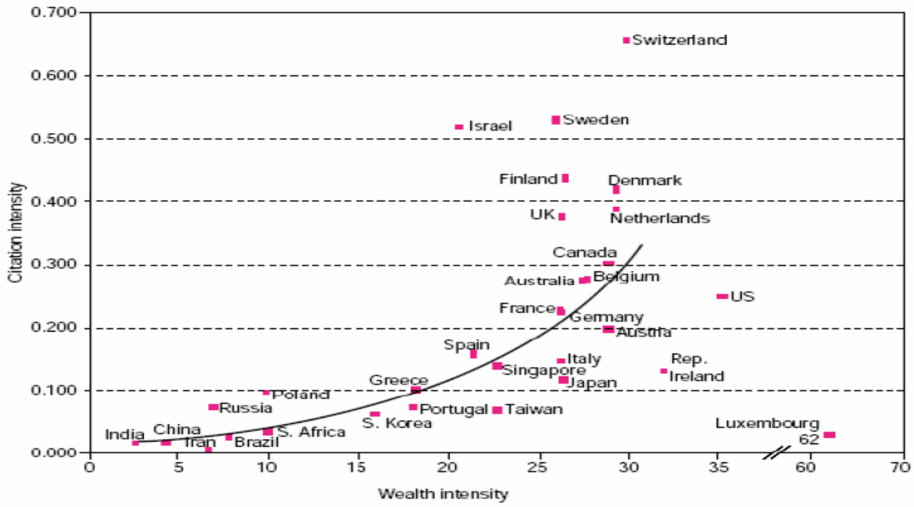

Fig. 1 Citations per person versus per capita GDP for 31 countries. Wealth intensity is in thousands of US dollars at 1995 purchasing-power parity. (Sources: Thompson ISI, OECD, and World Bank.)

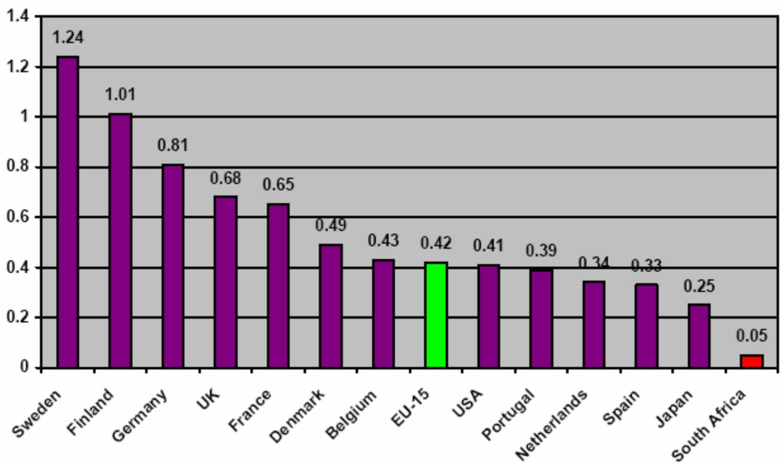

Table 1 Number of PhD's per thousand of the population

World Rank	Institution
1	Harvard Univ
2	Stanford Univ
3	Univ California - Berkeley
4	Univ Cambridge
5	Massachusetts Inst Tech (MIT)
6	California Inst Tech
7	Columbia Univ
8	Princeton Univ
9	Univ Chicago
10	Univ Oxford

In this ranking of universities, by Shanghai Jiao Tong University, the most highly ranked are all from rich countries. Africa has no university in the top two hundred. It is best to ignore these results when deciding on education policies because the results are very volatile in the sense that small changes in the metrics, the factors that determine ranking, can have large effects on the ranking. (The difference between a university ranked 200 and one ranked 300 is probably insignificant.) The main point is that the information in fig.1 and the tables is insufficient for the design of education policies because that information can not determine which of the statements (i), (ii) and (iii) is the most accurate. To make progress it is useful to explore the nature of the scientific enterprise.

The Pyramid of Science

The Law of the Vital Few (which is sometimes referred to as the 80-20 Rule, or Pareto's Principle) states that, in many activities and events, 80% of the effects come from 20% of the causes. Statistical analyses of the contents of numerous scientific journals indicate that a similar rule applies to science. Most of the papers that are published are of little value to the scientific community so that those papers are seldom, or never referenced. The papers that are cited often are relatively few in number, and are written by a relatively small number of scientists. The 80-20 Rule applies only approximately; a more accurate mathematical expression is the following: if the important papers are N in number then the total number of papers is on the order of NxN. Hence, out of a 100 papers in a journal, 10 will receive the most attention; out of a thousand, 30 will have that distinction. Similarly, if a university wishes to graduate 10 exceptional scientists it has to train on the order of 100 students (unless it is highly selective when choosing students.)

The structure of science is essentially that of a pyramid. At the top are the most productive scientists, the "Vital Few." They emerge from a large base of Ph.D scientists who in turn emerge from an even larger base of post-graduate, undergraduate, high and secondary schools students. This pyramidal structure sheds interesting light on the results in fig.1 and Tables 1 and 2. The universities listed in Table 2 are elite institutions, not only because their staffs include very productive scientists, but also because those universities attract exceptional students. (In some cases a mere 10% of those who apply are accepted.) The steady supply of highly talented young people is essential for the sustained success of those universities because some of the youngsters become innovators and entrepreneurs, giving rise to phenomena such as "silicon valley" in California. The universities provide the workforce for the companies, thus benefiting their countries and benefiting themselves – the students contribute to the endowments of their universities.

The peak of a pyramid may be its most prominent part, but is not an isolated feature and is totally dependent on a sound base beneath it. Of the three statements (i), (ii) and (iii) above, the third appears to be the most accurate. The implication is that, in a poor country where the alleviation of poverty is a high priority, any program to increase the number of Ph.D scientists must be part of a larger program that pays considerable attention to the lower parts of the pyramid, to the students in universities and schools. Scientists should be involved primarily in teaching and mentoring students, secondarily in writing papers. Is their an optimal number of PhD scientists for a country? What factors determine the number of scientists in a country?

The Shape of the Pyramid

The number of scientists in a country can obviously not exceed the total population. It is therefore intriguing that, for several centuries, in several countries, the number of scientists grew at an astonishingly rapid rate, far more rapidly than the human population. Starting in the mid-17th century the number of scientists doubled every fifteen years approximately, while the human population doubled every 50 years approximately. This result emerges from analyses of a variety of indicators of different aspects of science: the number of scientific papers published each year, of scientists writing those papers, of journals in which the papers appear, of the people receiving PhD's in science, and so on. Such a rapid growth in the number of scientists can not continue indefinitely so it is not surprising to see in fig. 2 below that the rate of growth has slowed down recently.

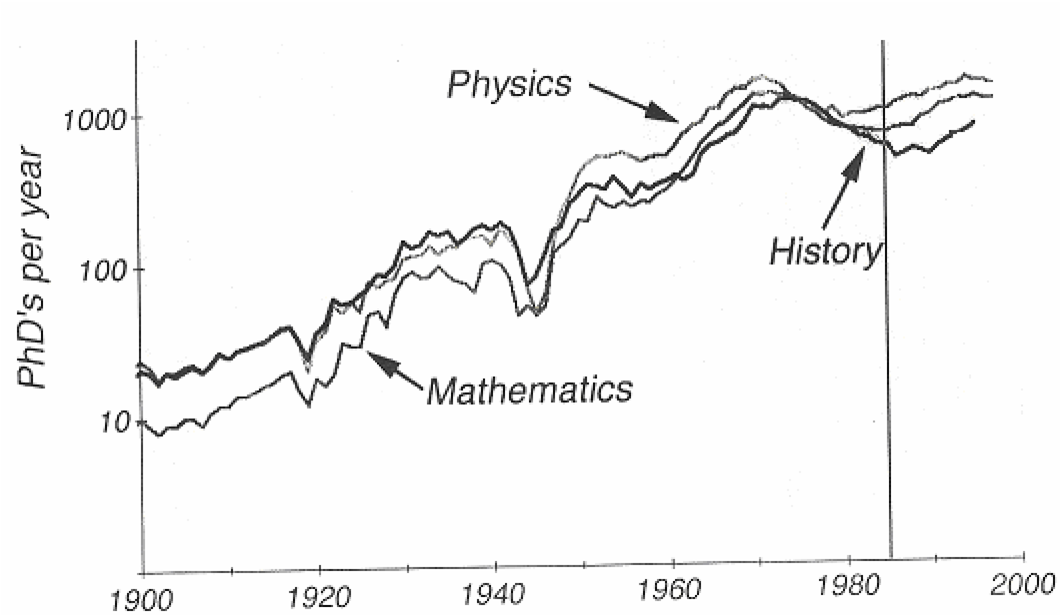

Fig. 2 The number of Ph.D degrees in mathematics, physics and history granted in the USA over the past century. (Source: Adkins, NSF, NCES)

In this and other similar graphs there is evidence that, since the 1970's, the rate of growth in the number of Ph.D's has slowed. Presumably an equilibrium will soon be reached with the number of scientists growing at the same rate as the population as a whole.

The surprising feature of fig.2 is the high correlation between the growth in the sciences and the humanities, a result that several other analyses confirm. This is unexpected because of a number of common perceptions: Sputnik, the Cold War, and the importance of the military-industrial complex all contributed to huge increases in the resources available to scientists; the rapid growth in certain fields, computer science and biology for example, gives the impression that growth is at a far more rapid rate in science than in the humanities. It is therefore surprising that, for several decades now, there has been parallel growth in the number of papers on E. coli, and on philosophy.

The resources available to scientists have indeed been increasing significantly, especially since World War II, but apparently universities have diffused those resources, allowing all disciplines, not only the sciences, to grow at the same rate. This suggests that the factor that has the strongest influence on the growth of disciplines, including the sciences, is the number of students enrolled at universities. (The number of mathematicians in a country is determined mainly by the number of students who have to take courses in calculus.) Over the past few centuries, the number of people attending universities has been growing at a much more rapid rate than the total population. In rich countries, that was the case into the 1970's but it appears that an equilibrium is being reached – see fig.2 -- and that, in future, universities will grow at the same rate as the total population

In the rich countries, the very rapid growth in the number of scientists (and more generally Ph.D's) is slowing down because there is no longer a rapid growth in the fraction of the population attending universities. In future, the rapid growth of universities is likely to occur in poor countries where, at present, a relatively small fraction of the population receives tertiary education. Of the students at universities, a tiny fraction will have exceptional scientific gifts. Hence the outstanding scientists of the next several generations will probably come from the developing rather than the developed countries. This, of course, can only happen if children in schools are provided with a good education, and if the gifted ones are identified and nurtured from an early age.

Comments relevant to South Africa

Up to the end of apartheid in 1994 South Africa had a strong scientific establishment based on only 10% of the population. The changes around that time, especially the emigration of large numbers of highly trained people, weakened science significantly but ushered in a new era with great potential because the pool of potential scientists increased enormously. Realization of that potential will take at least a generation because it requires a reform of education at all levels, from primary to tertiary. The reform has to involve more than changes in the curriculum; it requires changes in attitudes towards learning. The following incident clarifies this statement.

Why is summer warmer than winter? When a group of Harvard students, on their graduation day in 1986 was asked this question, most of them gave the wrong answer. To people in rich countries this incident was highly embarrassing because it happened at one of the most prestigious universities in the world. The considerable attention the incident received resulted in several projects to improve the teaching of science.

To people in poor countries the incident at Harvard is significant for different reasons. Apparently students at Harvard, and presumably other elite, highly ranked universities, do not learn very much science, but nonetheless continue with careers that provide them with a very high standard of living. Should we conclude that financial success does not depend on having even a modest knowledge of scientific facts and theories? What do the students at Harvard learn? An inability to answer a question about why summer is warmer than winter is not a significant disadvantage. However, an inability to find out the answer to that question is a serious handicap. Highly rated universities are important, not so much because the faculty publishes frequently cited papers, or because the students know the answers to many questions, but because the students learn how to find out the answers to questions. Those students learn how to use a scientific approach (of trial-and-error) when solving a problem, have access to knowledgeable people and to facilities (such as libraries), and above all acquire, from their teachers and fellow students, the self-confidence to address complex questions.

In 2007 the DNA pioneer and Nobel prize winner James Watson drew wide-spread condemnation for suggesting that black people are less intelligent than their white counterparts. Until 1994 such sentiments informed education policies in South Africa. To overcome the enormous harm those policies did, South Africa has to make special efforts to build the self-confidence of its students. They have the ability and talent; to succeed they need encouragement and opportunities.

Conclusions

Scientists with PhD degrees engage in two types of activities: (i) they teach and mentor students; (ii) they do research that results in published papers. The first is by far the more important activity because, without it, there would soon be no people to do research. Furthermore, the nature of science is such that research is an inefficient activity; most published papers are seldom or never referenced. Activity (ii) is subservient to (i) so that the number of scientists in a country is determined mainly by the number of students that needs to be taught. In wealthy countries where the competition for the best students is fierce, institutions use as a drawing card their scientists who publish frequently cited papers.

South Africa, with a serious shortage of technically trained people, faces a different challenge, that of attracting a large pool of students, not to a specific institution, but to science. To do so, the peak of the science pyramid should be clearly visible. Efforts to join the ranks of the elite universities of table 2 are laudable, but a more realistic alternative is to develop multi-institutional centres of excellence that take advantage of special research conditions in South Africa. Examples of such niches where South African scientists can excel in the international arena include the South Africa Large Telescope (SALT) project -- it exploits the southern skies – and the African Centre for Climate and Earth System Science (ACCESS) which exploits southern Africa's remarkable climatic diversity on land and especially at sea, in the three strikingly different surrounding oceans. Similar niches exist in several other fields.

The long-term prospects for science in South Africa are very exciting because the increase in the percentage of the population that attends universities over the next several decades implies a growing pool of students with exceptional talents for science. The teaching and mentoring of those students, at primary, secondary and tertiary levels, should receive the highest priority.

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