How many scientists does South Africa need?

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Education is critical to South Africa's efforts to alleviate poverty, the country's highest priority. But what is the relative importance of the elimination of illiteracy; the strengthening of primary, secondary and tertiary education; and of establishing centres of excellence devoted to research in certain scientific fields? Relevant to this question is that the wealth of a nation is correlated with the citations earned by the publications of its scientists: those scientists, normally with doctorates, are more numerous in rich than poor countries.

From this, it is often inferred (i) that 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. Consequently, poor countries should increase significantly their numbers of doctoral graduates.

But these inferences may not be valid, because correlations do not necessarily imply causality. An alternative inference may also be valid: (ii) rich countries can afford to employ many scientists whose publications increase the kudos 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 overeducated scientists with doctorates, who write papers that are mostly of academic interest.

Another possibility, falling between these two extremes (iii), is that scientists contribute to the wealth of a nation indirectly, by training exceptional students who create wealth by starting companies, for example such as Microsoft or Google. Hence the success of Ph.D. scientists should be measured, not in terms of their publications, but in terms of the success of the students their universities graduate.

The ranking of universities from around the globe, by Shanghai Jiao Tong University, receives enormous attention worldwide. Some people are concerned about Africa having no universities in the top two hundred,[1] although the difference between universities ranked 200 and 500 is probably insignificant, because small changes in the metrics (the factors that determine ranking), can have large effects on such large numbers. Of what significance is this ranking? If a country increases its number of highly ranked universities, does it follow that the achievement will contribute to the alleviation of poverty? Or will it merely add to the glory of the country, equivalent to winning medals at the Olympics? Given that beacons of excellence are important, what is the most effective way to establish such beacons?

Information concerning correlations between GDP and citation indices, and the ranking of universities, are insufficient for developing educational policies because that information cannot determine which of the inferences (i), (ii) and (iii) is the most accurate. To make progress it is useful to explore the nature of the scientific enterprise.[2]

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 and 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 of the order of $N \times N$. 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 in 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, secondary and primary schools students. Which group, in this pyramidal structure, contributes the most to the wealth of a country? Some people seem to think that the very productive scientists at highly ranked universities are the most valuable, but phenomena such as 'Silicon Valley' in California suggest that the students who become innovators and entrepreneurs are far more important. The scientists at the universities serve to attract the exceptional students to these universities. (At some universities a mere 10% of students who apply are accepted.) Those students, after they graduate, contribute to the endowment of the university. The professors therefore, indirectly, increase the endowment.

The peak of a pyramid, its most prominent part, is a beacon that can attract students 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 programme to increase the number of Ph.D. scientists must be part of a larger programme 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, and secondarily in writing papers. But is there an optimal number of Ph.D. scientists for a country? And which factors determine the number of scientists in a country?

The shape of the pyramid

For several centuries, in several countries, the number of scientists has grown far more rapidly than the human population. Starting in the mid-17th century the global number of scientists has doubled approximately every fifteen years, while the human population has doubled only approximately every 50 years. This result emerges from analyses of a variety of indicators of different aspects of science: the numbers respectively of scientific papers published each year; of scientists writing those papers; of journals in which the papers appear; of people receiving Ph.D.s in science, and so on.[2] Such a rapid growth in the number of scientists cannot continue indefinitely, so it is unsurprising that, in some wealthy countries, the rate of growth has recently slowed down. Presumably an equilibrium will soon be reached with the number of scientists growing at the same rate as the population as a whole. What is surprising is a high correlation between the growth in numbers of doctoral graduates in the sciences and the humanities. This notwithstanding the Sputnik, the Cold War, and the importance of the military-industrial complex all having contributed to huge increases in the resources available to scientists; and rapid growth in the importance of certain fields, such as computer science and biology. 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.[3]

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 1970s, but it appears that now an equilibrium is being reached and that in future universities will grow at the same rate as the total population.[3]

In rich countries, the very rapid growth in the number of scientists (and more generally in Ph.D.s) is slowing down, because there is no longer rapid growth in the proportion of the population attending universities. In future, 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, only a tiny fraction will have exceptional scientific ability. Hence the outstanding scientists of the next few generations will probably come from the developing, rather than the developed, countries. This, of course, can happen only 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. Realisation of that potential will take at least a generation because it requires 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.[4]

To people in poor countries, the incident at Harvard is significant for different reasons. Apparently students at Harvard, and presumably from 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?

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, and have access to knowledgeable people and to facilities (such as libraries). Above all the students acquire, from their teachers and fellow students, the self-confidence to address complex questions.

In 2007 the DNA pioneer and Nobel laureate James Watson drew widespread 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. The high rate at which students drop out of universities before they graduate suggests that students receive inadequate mentoring.

Conclusions

Scientists with Ph.D. degrees engage in two major activities: (i) teaching and mentoring students; and (ii) conducting 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 how many students need 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 the world 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 Southern African Large Telescope project—which exploits the southern skies—and the African Centre for Climate and Earth System Science (http://www.Africaclimatescience.org), which capitalises on southern Africa's remarkable climatic diversity, both on land and in the surrounding oceans. At present possible climate changes associated with global warming receive considerable attention. An appropriate response has to include promotion of the excellent educational opportunities global warming presents to learn about science in general, and the earth sciences in particular.

The long-term prospects for science in South Africa are very exciting because the increase in the percentage of the population attending university over the next few 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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