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# From Little Science to Big Science

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# From Little Science to Big Science

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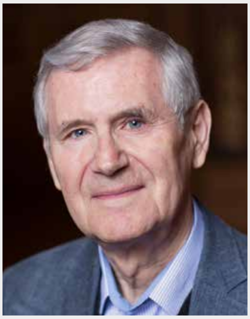
The number of scientists has been increasing exponentially for at least a century, with doubling times ranging from 10 to 15 years. The needs of the scientific enterprise are now beginning to strain or even overwhelm national resources and are irreversibly transforming science's soul. Not all changes are for the worse, but it is becoming increasingly difficult to maintain scientific integrity, fair quality control and the spirit of cooperation within the scientific community. Coming to terms with Big Science is one of the major challenges of the next scientific generation.



Gottfried Schatz was born on 18 August 1936 in Strem, Austria. He was professor of biochemistry at Cornell University, USA, and from 1974 he was at the Biozentrum at the University of Basel. After reaching emeritus status in 2000, he served as president of the Swiss Science and Technology Council. Gottfried Schatz was a world leader in mitochondrial research, the study of the power plants of cells, and a passionate advocate of interdisciplinary research. He prepared the following manuscript for a keynote lecture that he intended to give on 24 September 2015 at ScienceComm, the Swiss annual congress of science communication. Because he was unable to attend in person, he provided the manuscript to be distributed at the conference. Gottfried Schatz passed away on 1 October 2015.

## From Little Science to Big Science

During the past decades, science has changed profoundly in several ways. Some of these changes have been for the better, but some of them have led to severe problems. I will touch on two of these problems and suggest ways to deal with them.

The first problem is the blurred distinction between knowledge and science. The two are now widely viewed as synonyms – as identical enterprises that share the same mission. And since fulfilling this mission is expensive, the public wants to steer the world of science and knowledge as precisely as it can.

This confusion of knowledge with science distorts reality and causes many of the difficulties we scientists are struggling with today. Science and knowledge have different characters and must be fostered in different ways. After all, the main business of science is not knowledge but ignorance. Researchers try to convert ignorance into knowledge and are usually much more interested in the act of conversion than in the product. Most full-blooded researchers consider the knowledge they create almost as a by-product and are happy to leave its teaching and safekeeping to others. To them, a textbook of biochemistry is not biochemistry, it is the history of biochemistry – a summary of what they already know or at least should know. True biochemistry would be a revealing discussion in the laboratory, a seminar on a new discovery, or a helpful hint from a colleague. The home of a true researcher is not the safe haven of proven knowledge but its outermost fringe, where knowledge fades into ignorance.

Scientific knowledge is not a commodity we can neatly wrap up, label, and store forever in numbered bins. It resembles a zoo of wild animals that tear at their confines, break through the walls of their cages, and interbreed into completely unexpected new creatures. Jean Paul Sartre once said, «It is not we who make war; war makes us.» The same is true of our scientific knowledge. It changes continuously and thereby changes us. We may be able to control it briefly, but in the long run knowledge always wins. It obeys its own laws, which we do not fully understand and which we cannot control. The famous Victor Hugo quote «Nothing is as irresistible as an idea whose time has come» is probably not authentic, but it is nevertheless true.

In the real world, most scientists deal with the administration and teaching of scientific knowledge. Only a small minority, the active researchers, transform ignorance into knowledge. And among these active researchers there is a tiny minority of exceptionally creative minds who achieve the ultimate goal of science: to create new ignorance, to discover something that we did not know that we did not know. When Gregor Mendel discovered the units of inheritance, Sigmund Freud the subconscious, or Max Planck the energy quantum, they opened up vast new continents of ignorance that invited exploration and forever changed our view of us and the world.

We researchers are not too much disturbed by the ephemeral nature of scientific knowledge. Our relationship to knowledge has always been ambivalent: we want to create it, but once we have created it, we distrust it and try to prove it wrong. Owning knowledge is less important to us than the conviction that we can always create new knowledge by observation and critical thinking. Existing knowledge is a child of the past and will never, by itself, allow us to confront an ever-changing world. If we want to master the future, we must rely on the youthful force of scientific discovery. We need people who see what everybody sees, but think what nobody has thought before. We need people who discover intuitively that the path from A to C does not lead via B, as everybody thinks, but via X or Z. We need courageous minds who are not afraid to set sail for faraway and possibly dangerous waters if they hold the promise of discovery. The American writer John A. Shedd said it as follows: «A ship in harbor is safe. But that's not what ships are made for.»

Knowledge is important, but we tend to overrate it. This is true for our kindergartens, our schools, our universities, and our national research bureaucracies. Our teaching institutions put too much emphasis on memorizing existing knowledge and thereby stifle critical scientific thinking. And our national research bureaucracies have tried to tell researchers what knowledge they should create for the public good. Such an attitude does not recognize the fact that knowledge and science are sisters, but that these two sisters have very different characters. They often stand in each other's way and sometimes even fight one other. For example, the safekeeping and teaching of knowledge benefit from strict organization, but this is not true of science. The legitimate goal of any system of organization is to prevent unexpected developments, mistakes, and exceptions. But unexpected developments, mistakes, and exceptions are at the very heart of innovative science. That's why organization and scientific innovation are inherent adversaries and must be carefully balanced against each other. A similar thing may be said for coordination. Many countries try to coordinate their research efforts as much as possible, yet scientific innovation is driven by individuals who think against the grain and have the courage to swim against the stream. We must never forget that organization is the enemy of innovation and coordination is the enemy of motivation.

The second problem I would like to address has to do with sheer numbers. Today there are about 10 to 20 times more scientists than when I started out in science. Or, to put it differently, 80% to 90% of all scientists who have ever lived are living today – and 80% to 90% of all research findings ever published will be published during our lifetime. Every decade now produces as many new scientists as have ever lived before. It is no wonder that we have become myopic for science's past achievements. A ten- to twenty-fold quantitative change invariably leads to a profound qualitative change, be it the biosphere, the economy, or science. Little Science has turned into Big Science, thus changing its soul.

Big Science was not born as the result of specific decisions or events such as the Manhattan Project or the Apollo moon program but evolved gradually from Little Science. This evolution, like most evolutions, accelerated exponentially. Scientific information and the number of scientists have been increasing exponentially at least since 1920 and probably since the middle of the 18th century. The constancy of this exponential growth approaches the rigor of an empirical law, with doubling times ranging from 10 to 15 years. Growth seemed barely noticeable at first but has now reached the so-called knee of the exponential curve, at which any further increase suddenly challenges or even overwhelms the available resources. In technology, the increase in people and information may now even be hyperbolic, which means that each doubling time is only a fraction of the preceding doubling time. Growth of the scientific enterprise has been much faster than that of the world population or gross national products, whose doubling times have generally been around 50 and 20 years, respectively. Exponential growth usually creates new problems faster than one can solve them and eventually hits a limit. That's what happened to physics a few decades ago, and that's what is happening to the biological sciences right now. The different branches of science each have their own life cycle, but these individual cycles are only minor bumps in the smooth exponential increase of science as a whole.

Big Science is no longer a calling of the few but a huge professional enterprise that strains the resources even of wealthy nations. The scientific community has turned into a «workforce» subjected to a myriad of rules, regulations, and policies; postdocs and graduate students form «unions» demanding formal «mentoring agreements»; and our science curricula teach scientific facts, technical tricks, «professional ethics», and «research responsibility» but not what science is, what it demands from us, and how it changes our view of us and the world. Big Science is dominated by the well-trained but uneducated scientist.

Big Science has intensified the fight for attention, which now often does not go to the best but the loudest. Speed seems more important than quality. According to recent studies, at least two-thirds of all biomedical research findings cannot be reproduced, causing a huge waste of time and money as well as a disturbing drop in the success rate of clinical phase II trials. In the «hot» field of cancer drug targets, the reproducibility of published findings is particularly low and shows no significant correlation with journal impact factor or the number of confirming publications by others. It has even been argued that most biomedical research findings are probably false. Many pharmaceutical companies no longer take the results of academic research at face value but verify them in-house or through contract laboratories before using them as a basis for drug development. There are many reasons for this malaise: artefacts from applying ever more sensitive analytical methods to ever more complex biological systems; sloppy workmanship caused by the «getting scooped» or the «publish or perish» syndromes; unwitting group bias pervading research networks; improper statistics; financial interests – and fraud.

Science needs competition, but competition has become so fierce that many fields of science have turned into war zones. Nothing illustrates this better than the current crisis of peer review. When I now serve as editor for so-called prestigious journals, I am appalled by the ferocity of some of the reviews that cross my desk. Instead of providing helpful criticism, they seem intent on killing the manuscript. It does not help that many journals encourage their editors to reject a certain minimum percentage of all submissions without sending them out for external review. Reviewers now rarely find the time to go through a manuscript with the required care, and so it comes as no surprise that peer review is all too often ineffective in safeguarding the quality or the reliability of scientific literature.

Many scientists are no longer willing to put up with needlessly aggressive and venomous peer review and the perceived tyranny of so-called luxury journals. There is no single solution to this vexing problem, but the advent of electronic publishing would allow peers to add anonymous or signed comments to a paper after its publication. Post-publication peer review used to be common in the past, particularly in the humanities. Post-publication comments on the inability to reproduce a published result would also provide a much-needed platform for communicating negative findings. Conversely, a validation statement by an independent research group or by a commercial validation agency could enhance a paper's credibility.

Nobody senses the pressure exerted by Big Science more acutely than those who work for the review panels of national or international granting agencies. Again, there are no quick fixes, but granting agencies should do everything they can to minimize the amount of paperwork for applicants. For example, if someone has had a grant for the past five or six years, the publications from the preceding grant period are much more informative than the research proposal itself. Why not ask applicants to submit only a very brief one- to two-page research proposal together with two or three of the best papers they published during the preceding grant period? Reading these papers carefully should reveal more about the applicant than reading a massive grant application and a long list of publications. This procedure alone could reduce the workload of grant reviewers significantly. A similar approach could also streamline the evaluation process for promotions, prizes, or academic positions.

Many problems of Big Science stem from the fact that too many researchers compete for insufficient resources. One way to address this problem might be to train fewer graduate students. We should continue to train as many scientists as possible because there is a painful shortage of scientifically trained minds in our schools, our administrations, and our political leadership. But these scientists need not have the urge or the talent for a successful research career. They do not need to have doctorates. That's why we should allow only our very best students to get a doctorate as a first step to entering research. A proven quality control filter is a departmental graduate program in which doctoral students are selected by the entire department rather than by individual professors. Many universities claim to have graduate programs, but most of them are only cheap imitations of the real thing.

It would be foolish to think that we can roll back time and return to an era of quiet scientific reflection and sufficient funds. First, such an era has never existed. And second, Big Science will remain big or even grow in spite of all our efforts to prevent it. But we must be honest enough to acknowledge that science is in a crisis and we must stand up against the problems Big Science has brought us.