Measuring Science, Technology, and Innovation: A Review

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ABSTRACT

The measurement of scientific, technological, and innovative activities (STI) in the economy is an increasing challenge faced by statistical agencies around the world. In this review, we survey the current state of the art. We discuss the concept of indicators, their quality and use, and present a schematic model of the STI system that can help us identify gaps in the set of indicators commonly in use. We then review the developments in STI measurement that have taken place in the rest of the world, particularly the widespread use of innovation surveys. The monograph concludes with a discussion of the measurement gaps and issues in the U.S., which we identify as innovation (especially in the service sector), non-R&D investment related to innovation, data timeliness, data linkages, measurement related to public policy goals, and the sources of capital for innovation.

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What is an indicator?

An "indicator" is a set of facts or observations that tells us something meaningful about the underlying phenomenon of interest, in this case science, technology and innovation (henceforth STI). In order to evaluate whether a particular set of facts is a good indicator, or to determine whether there are indicators we should have that we do not, we need to consider in some detail what makes a particular set of facts *meaningful*. In this section we address the important dimensions that affect the meaning and usefulness of an indicator.

The foundation of an indicator is a set of data. The word "data" is a plural of the Latin *datum* meaning "given." We frequently think of data in the form of numbers, but conceptually data can be either quantitative or qualitative. Either way, formal analysis of data is predicated on the idea that the data are, indeed, given, meaning that they are generated by the world itself rather than created by the people who want to use them. In reality, what we call "data" in most contexts are numbers or qualitative observations that are usually collected by human beings, and the nature of this collection process combines with the "givens" of the world to determine what are recorded as "data."

For many purposes – particularly their use by policy makers and other "lay" people concerned about science, technology and innovation – presentation of data without further processing does not constitute a meaningful indicator. All of the indicators published by NSF are constructed in some way from underlying data. So any recommendation about an indicator is, in a sense, a compound recommendation: (1) what data should be collected, and (2) how should those data be summarized in a published indicator or indicators?[1]

The relationship between indicators and a framework for analysis of STI

In order to determine whether an indicator is meaningful, we need to assess both the data that are used, and the manner in which those data are summarized. Carrying out this assessment requires specification of the underlying concept we are trying to understand, and the relationship between this concept and the process that generates the data. For example, we tabulate how many academic degrees of various kinds are granted each year. We don't really care about degrees per se, but we care in some way about the knowledge and skills of the population, and we believe that the number of degrees granted and the fields in which they are granted is in some way informative about the accumulation of knowledge and skills. We measure income in various ways. For some purposes, we might care about income itself, but more often we are using income as an indicator of well-being or happiness or success. Sometimes the proxy nature of our measurements is explicit; in other cases it is implicit. But either way, we cannot assess how meaningful an indicator is without thinking about its relationship to the concept or concepts that we really care about.

But where does the statement "the number of degrees granted is in some way informative about the accumulation of knowledge and skill"

[1] Data collected by the government are also used in disaggregated form (i.e. without creation of summary indicators) by social scientists and others interested in studying the underlying phenomena. We return below to the importance of the inter-relationship between the collection of data in support of indicators, and the use of data for research.

come from? And why do we think that the population's accumulation of knowledge and skill is itself something we care about? The determination of both what aspects of the real world matter, and what measurements are illuminating with respect to these aspects will be based on some kind of framework, either explicit or implicit. A framework is an abstract representation of the world, typically focusing on one or a small set of aspects (e.g. science, technology and innovation). Such a framework can be constructed and described in a variety of ways: economists like to use symbols and equations; anthropologists tend to use words; systems engineers frequently use diagrams. Whatever the mode of presentation, the framework is designed to capture the essence of the underlying complex reality. Even if such a framework is not fully articulated, it will underlie the choice of data collected and the interpretation placed on the resulting indicators. In this report, we make the framework we are using explicit, because we believe that leads to greater clarity.

Having a framework for analysis is also important for the question of how data and indicators can inform public and private decision-making. In order to use data to inform decisions, we again need an understanding of what those data tell us about the workings of the STI system. Either explicitly or implicitly, we have some kind of framework in which those data relate to the instruments or the goals of our decisions. Again, we believe that being explicit about the framework leads to greater clarity in understanding how the data or indicators relate to the goals and instruments of policy.

Note that the relationship between any framework for analysis and data is an iterative one. We need some kind of framework to organize ideas and to know what data we should be looking for, and to support interpretations of the data that we see. At the same time, social scientists and others will use the data to test various models, by studying the extent to which the predictions of their models are borne out in the data. This process may suggest changes to the framework used and also to the data that is needed for analysis. We return below to the implications of this two-way relationship between the data and the model.

In Section 2, we summarize the framework for analysis of the STI system that is most widely used by economists. In this framework, for example, the level of knowledge and skills of the population is important for several reasons: it affects the amount of goods and services that can be produced per capita, and it also affects the rate at which *new* knowledge is produced, which affects the improvement over time in the amount of goods and services that can be produced. In Section 3, we take the next step, and consider how the specific data currently collected by the U.S. government, and indicators constructed from those data, relate to the important concepts within the framework. Section 4 expands this discussion by reviewing data collected and indicators published by other countries and international organizations. Section 5 then turns to the issues of policy, and draws explicit connections between important policy questions and indicators, using the framework of Section 2. Section 6 then builds on these discussions to highlight gaps and issues with the existing indicators. Section 7 provides concluding comments.

Uses of STI indicators

In addition to understanding the data underlying an indicator, how those data were processed, and the relationship of the data and its processing to a framework for analysis of the STI system, evaluating indicators also requires an understanding of the purposes for which they are used.

Performance assessment and benchmarking

Some indicators serve as performance measures that give an assessment of whether the STI system or some component thereof is doing better or worse over time, and better or worse than some comparison group (e.g. other countries). For this purpose, the indicator may stand for some aspect of the system that is intrinsically valued (e.g. income), or it may stand for an aspect of the system that, within the framework, is understood to have important impacts on aspects that are valued. For example, past research has suggested that, all else equal, a greater intensity of investment in new knowledge will lead to higher rates of productivity growth and income growth. For this reason, one might focus on the R&D/GDP ratio over time or across countries as a benchmark of innovative activity. But in doing so, one should always keep in mind the role of knowledge investment in the framework, and the relationship between the framework concept of knowledge investment, and the R&D data that are actually collected. In this example, it is clear that spending on R&D may not capture all of the investments that are directed towards creating new knowledge (and may capture some investment that is not thus directed). In addition, the share of innovation-related investment captured by an R&D measure may be changing over time so that the measure is potentially misleading taken on its own. The framework also makes clear that there is no particular level for this ratio (such as 3%) that is optimal. Finally, even though the relationship between R&D investment and productivity growth is well established, it is still true that R&D investment is an indicator of innovative activity, not an indicator of innovation, which is the concept we think is more closely associated with the growth outcomes of interest.

Informing public policy decisions

An important function of STI indicators is to provide an informed basis for public policy decisions. But of course policy is not intended to affect the indicators, it is intended to affect the underlying concepts of interest. So to determine if a suite of indicators is well-suited to inform public policy, one needs to identify the goals of public policy, and to use the framework for analysis of STI to understand how those goals relate to data that can be collected. We discuss these issues in Section 5.

Informing private sector decision-making

Firms and individuals in the for-profit sector also use STI indicators to make business decisions, and not-for-profit organizations (e.g. universities) use them to make decisions in pursuit of their missions. It is unclear to what extent these parties needs and desires are different from those of policymakers, and, if they do differ significantly, to what extent these distinct needs are considered in the decisions made by government statistical agencies about the STI indicators system.

Facilitating social science research

As noted above, social scientists use data to test the implications of models, and thereby refine the models. Hence their interest in the indicators endeavor is more in the collection and availability of data than in indicators *per se*. But because model testing and validation is so important, we will comment in the concluding section on how the needs of social scientists might be considered in the context of recommendations about indicators.

Issues of data collection and indicator construction

As noted above, though formal statistical theory treats data as "given," in reality the potentially messy process by which the data are created and compiled is sometimes important in evaluating indicators. In this section we identify a few basic issues.

Data dimensions

Data collected to construct indicators may span time, space and institutional categories. Construction of summaries to be reported as indicators can then be aggregated along one or more of these dimensions, depending on the purpose of the indicators. Reporting of indicator values in a time series is frequently of interest; this raises issues of consistency of interpretation of the summary values based on data collected at different points in time. Comparisons across different geographic areas, or across different categories of institutions (e.g. small firms versus large firms), are also of interest. When comparing data from the same point in time, but different institutions or geographic areas, there is an issue of comparability that is analogous to the consistency issue when comparing over time. For analytical purposes, it is often useful to be able to construct a *panel*, in which the indicator of interest varies across both time and another dimension such as geography or institution type.[2] The need for comparability can come into conflict with the need to

[2] For micro-data analyses, it is often valuable to have access to longitudinal data, in which data from the same individuals or institutions is collected at multiple points in time.

redesign surveys and data collection methods in response to a changing landscape, especially in the case of indicators describing innovation.

How the data were generated

Some data collected for use in STI indicators are generated by companies or other organizations in the normal course of their business for their own internal use; some are also generated by these organizations for other external reporting requirements (e.g. financial reporting required by Generally Accepted Accounting Practices). Other data are generated by organizations specifically in response to government requests tied to STI data collection. The advantage of using data otherwise generated in the course of business is that it may be less burdensome for the entities involved. Also, the intrinsic importance of the data elements to the organizations may lead to greater care and consistency in construction, compared to data that are generated only because NSF asks for them. On the other hand, precisely because the data are created for other purposes, they may be less ideally suited to the intended purpose than data that can be specified with their intended STI indicator use in mind.

How the data are collected

For data that are generated for other purposes, there is also a potential distinction between data that are collected by explicit survey requests to the entities that created the data, and data that can be collected passively, i.e. without the active assistance of the generating entities. Examples of passive collection include mining of data from reports filed by companies with agencies such as the SEC or IRS, and “scraping” of data from websites. The advantage of passive collection is minimization of burden on the generating entities. In some cases, there may also be an advantage inherent in the absence of an opportunity for the entities that generate the data to manipulate strategically what is reported. On the other hand, when passively collecting data generated for other purposes, it may be difficult to understand fully what the data really mean and difficult to control the sampling frame to ensure representativenes.

Public versus private data collection

When we speak of indicators, we tend to think of data collected and published by the government. But social science researchers can and do collect data themselves. What is the appropriate mix of government and non-government collection of data and publication of indicators? Data that are of wide potential use have an important public-good attribute. But researchers studying STI can apply for public funding of their research, thus solving the public good aspect of the problem without having the government be the party that collects and publishes the data and indicators. The government does have particular advantages as data collector, where the data in question are related to other data that the government collects for statutory purposes (e.g. census data), and/or the data are considered proprietary and therefore unlikely to be provided by private agents without government mandate. But, by definition, this mandatory data collection principle can only be applied to a limited number of data elements. Recognizing the scope for individual investigators to collect a variety of information beyond what is collected by the government greatly increases the potential scope of indicators available to public and private decision-makers. This is particularly true with respect to data that can be collected passively, as discussed above, because in such a case the requirement of mandatory compliance that the government can bring to its surveys is not necessary. Thus, in considering the possibilities that may be created for additional indicators by passive data collection, we should not assume that these data have to be collected and published by the government. There is considerable scope for individual researchers, probably with public research funding, to collect and publish such data.

Data quality

Before moving on to the framework for analysis of indicators within the STI system, we pause briefly to review measurement issues and how they affect the quality of data. This section draws heavily on Griliches (1986), which can be consulted for more detail.

Griliches categorizes issues of data quality as falling into three categories: extent, reliability and validity. Extent refers to the scale and scope of the data: for how many years has it been collected, how many different data items are collected, and how broad is the coverage in terms of regions or types of institutions. With respect to extent, more is better, in a fairly straightforward way.

Reliability refers to the inherent reproducibility of the data collection process itself. In effect, it asks, if the data were collected on different occasions or in different places, and nothing real about the world were different in the two times or places, how close would the different data be to each other? They won't typically be the same, because each measurement includes random sampling error. Reliability is a measure of the signal-to-noise ratio, i.e., the fraction of the variance in the data that is systematic rather than random.

Validity refers to the extent to which the data are generated and collected in a manner that makes them correspond closely to the underlying concept that we care about. Griliches subdivides validity into considerations of relevance and representativeness. Relevance is, in essence, the question of the extent to which what we are measuring is closely related to what we care about. Representativeness arises in any context in which we collect only a data sample, i.e. we do not collect data from all relevant individuals or units. It refers to the extent to which the different kinds of units had the same probability of contributing to the data (or if the probabilities differed, they did so in a systematic way that we can account for).

To illustrate these concepts, consider the NSF industrial R&D survey. It is very extensive, because it goes back many decades, and covers all firms and all parts of the country. It is reliable, in part because it is so extensive, and in part because the definitions and procedures are well established and understood. But how valid it is really is a question of what underlying STI concept you wish to use it to measure. Its relevance is potentially questionable, because it looks only at formal R&D activities, which may not be the right thing to look at if what we care about is overall knowledge investment. In the past (prior to redesigns in 1992 and 1995) its representativeness may have been questionable, because the sampling frames failed to adequately sample small and medium-sized firms and firms in the service sector.[3] These observations don't mean the data are useless; they simply make the point that the validity of a set of data can only be judged in the context of the framework for analysis of STI and the role to be played by those data within the framework.

As noted above, there is variation in the extent to which the potential gap between the measured item and the model concept is explicitly acknowledged. Virtually everyone who uses patent statistics to measure the rate of invention or innovation notes explicitly that patents are only a "proxy" for the underlying concept. But the issue of proxies is really more one of degree than of kind: for virtually every indicator we use we must acknowledge some degree of potential distance between the measurement and the concept it stands for. Rather than viewing "proxy" as a mild epithet that applies to some indicators but not others, it makes more sense to consider, in all cases, the extent to which a particular indicator might deviate from the underlying concept for which it stands.

It is also worthwhile to consider how the choice of indicators and method of data collection affects their reliability and validity. As noted above, there may be significant benefits in terms of government resources and burden on private parties to expanding the use of data that is passively collected through methods such as web scraping, instead of government surveys. With statistically designed surveys, however, we have both a high degree of reliability, and, perhaps more important, a clear understanding of the level of reliability and possible sources of unreliability. With passive methods, it may be much harder to assess reliability, precisely because the relationship between the captured data and the universe of underlying activity is not known.

Finally, collection of data for indicators has to be sensitive to a variety of different ways in which the collection itself may affect behavior and thereby change the data. The "Hawthorne effect," whereby the mere act of observation may cause people to behave differently, has been understood for some time. In this neutral form, it is not necessarily

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[3] See the NSF website for information on the changes in sampling during the 1990s. http://www.nsf.gov/statistics/nsf02312/sectb.htm

assumed that one can predict the nature or direction of the change in behavior that results from observation. A more complex and dangerous problem arises from the combination of data that are imperfect proxies for an underlying behavior, with the use of those data to evaluate and reward the people who generate the data.

For example, it is entirely reasonable to use numbers of published papers and citations as a proxy for the generation of new knowledge. We know that the relationship between the proxy and the underlying phenomenon is imperfect, but as long as the relationship is stable across both time and context, it can be useful indicator. Even if there are differences in the relationship in different times or different contexts, it may still be a useful indicator if we know what those differences are, or can use statistical methods incorporating additional information to correct for them. But if we increase our reliance on such data for the purpose of evaluating and rewarding individuals or organizations, they will then have an incentive to generate more papers *relative to* the rate at which they are generating new knowledge. This can easily generate changes over time in the relationship between the data and the concept of interest, and the extent of these changes may vary across institutional contexts. These effects then make the proxy indicator less informative about the underlying phenomenon of interest.

There is no total solution to this problem, because, as noted above, virtually all indicators are to some degree proxies that may diverge from the underlying concept of interest. But some may be less subject to this kind of endogenous distortion than others. It is also possible that this consideration should weigh in favor of passive data collection rather than surveys, to the extent that people are more likely to respond to the possible incentives created by data collection if they themselves are active participants in its collection.

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