Improving Reproducibility and Replicability in Research

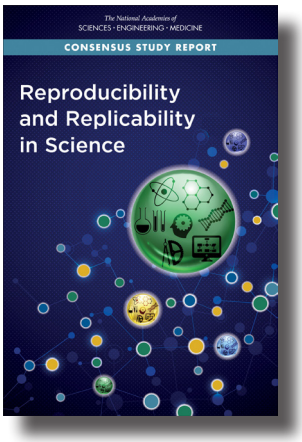
HIGHLIGHTS FROM THREE NATIONAL ACADEMIES REPORTS

One of the pathways by which scientists confirm the validity of a new finding or discovery is by repeating the research that produced it. The scientific enterprise depends on the ability to scrutinize scientific claims and to gain confidence in results that have stood up to repeated testing. In recent years, concerns over the reproducibility and replicability of scientific research have been expressed in both scientific and popular media.

Three recent reports from the National Academies of Sciences, Engineering, and Medicine examine this issue and recommend actions that can improve reproducibility and replicability in research:

- *Reproducibility and Replicability in Science* (2019)
- *Open Science by Design: Realizing a Vision for 21st Century Research* (2018)
- *Fostering Integrity in Research* (2017)

All three reports emphasize that there is a strong connection between openness and transparency and more reliable and trusted science. Transparency about methods, data, computer code, and other aspects of research is crucial to efforts to reproduce and replicate research. Persistent efforts by many stake holders—researchers, research institutions, funders, and publishers—will be needed to move the research enterprise toward greater openness and transparency in ways that support reproducibility and replicability.



REPRODUCIBILITY AND REPLICABILITY IN SCIENCE

This congressionally requested report assesses reproducibility and replicability in science and provides findings and recommendations for improving rigor and transparency in research.

While the terms "reproducibility" and "replicability" are often used interchangeably, this report defines them as separate concepts. **Reproducibility** means computational reproducibility—obtaining consistent computational results using the same input data, computational steps, methods, code, and conditions of analysis. **Replicability** means obtaining consistent results across studies aimed at answering the same scientific question, each of which has obtained its own data. In short, reproducing research involves using the original data and code, while replicating research involves new data collection and similar methods used by previous studies.

These two processes also differ in the type of results that should be expected. In general, when a researcher transparently reports a study and has made available the underlying digital artifacts, such as data and code, the results should be computationally reproducible. In contrast, even when a study was rigorously conducted according to best practices, correctly analyzed, and transparently reported, it may fail to be replicated.

Reproducibility. The report's definition of reproducibility focuses on computation because the abundance of data and widespread use of computation have transformed many disciplines. However, this revolution is not yet uniformly reflected in how researchers use software and how scientific results are published and shared. These shortfalls have implications for reproducibility, because researchers who wish to reproduce previous results may lack the information or training they need to do so. To help ensure the reproducibility of computational results, researchers should convey clear, specific, and complete information about data, code, models, and computational methods and analysis that support their published results.

Replicability. One important way to confirm or build on previous results is to follow the same methods, obtain new data, and see if the results are consistent with the original ones. However, a successful replication does not guarantee that the original scientific results of a study were correct, nor does a single failed replication conclusively refute the original claims. Non-replicability can arise from a number of sources—some that are potentially helpful to gaining knowledge, and some that are unhelpful.

Potentially helpful sources of non-replicability include inherent but uncharacterized uncertainties in the system being studied. These sources of non-replicability are a normal part of the scientific process, due to the intrinsic variation or complexity in nature, the scope of current scientific knowledge, and the limits of our current technologies. In such cases, a failure to replicate may lead to the discovery of new phenomena or new insights about variability in the system being studied.

In other cases, non-replicability is due to shortcomings in the design, conduct, and communication of a study. Whether arising from lack of knowledge, perverse incentives, sloppiness, or bias, these unhelpful sources of non-replicability reduce the efficiency of scientific progress. Unhelpful sources of non-replicability can be minimized through initiatives and practices aimed at improving research design and methodology through training and mentoring, repeating experiments before publication, rigorous peer review, utilizing tools for checking analysis and results, and better transparency in reporting.

Improving reproducibility and replicability. The report recommends a range of steps that stakeholders in the research enterprise should take to improve reproducibility and replicability:

- All researchers should include a clear, specific, and complete description of how the reported results were reached. Reports should include details appropriate for the type of research, including:
  - a clear description of all methods, instruments, materials, procedures, measurements, and other variables involved in the study;
  - a clear description of the analysis of data and decisions for exclusion of some data or inclusion of other;
  - for results that depend on statistical inference, a description of the analytic decisions and when these decisions were made and whether the study is exploratory or confirmatory;
  - a discussion of the expected constraints on generality, such as which methodological features the authors think could be varied without affecting the result and which must remain constant;
  - reporting of precision or statistical power; and
  - a discussion of the uncertainty of the measurements, results, and inferences.
- Funding agencies and organizations should consider investing in research and development of open-source, usable tools and infrastructure that support reproducibility for a broad range of studies across different domains in a seamless fashion. Concurrently, investments would be helpful in outreach to inform and train researchers on best practices and how to use these tools.
- Journals should consider ways to ensure computational reproducibility for publications that make claims based on computations, to the extent ethically and legally possible.
- The National Science Foundation (NSF) should take steps to facilitate the transparent sharing and availability of digital artifacts, such as data and code, for NSF-funded studies. This includes developing a set of criteria for trusted open repositories to be used by the scientific community for objects of the scholarly record, endorsing or considering the creation of code and data repositories for long-term archiving, and preservation of digital artifacts that support claims made in the scholarly record based on NSF-funded research, among other actions.

Reproducibility and Replicability in Science can be downloaded free of charge at https://www.nap.edu/catalog/25303.

OPEN SCIENCE BY DESIGN: REALIZING A VISION FOR 21ST CENTURY RESEARCH

This report offers guidance to the research community as it builds strategies for achieving open science. Open science aims to ensure the free availability of scholarly publications, the data that result from research, and the methodologies, including code or algorithms, that were used to generate those data. One of the benefits of open science is rigor and reliability, since standards for data and code sharing make it easier for researchers to reproduce and replicate reported work.

The report offers a vision called Open Science by Design—principles and practices that should occur at each stage of the research process–provocation, ideation, knowledge generation, validation, dissemination, and preservation. For example, at the "validation" phase of the research process, researchers use open data techniques to analyze, interpret, and validate findings. They may present their preliminary findings at conferences and refine their methods based on relevant comments and critiques. They may deposit their initial working paper in a preprint server and revise the paper based on the open peer review afforded by the service. They prepare their data in standard formats according to disciplinary standards and describe both data and analytical code in optimal ways for reuse and replication.

The principle for openness of data and other information underlying reported results is that they should be available no later than the time of publication, or when the researcher is seeking to gain credit for the work. Sharing prior to the point of publication is up to the researcher, who is in full control of the decision when to share.

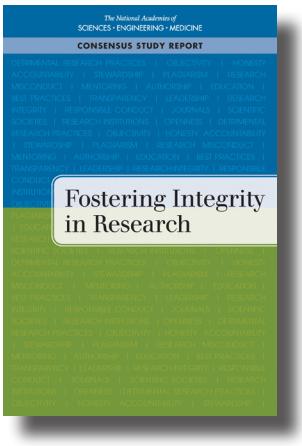
Many barriers remain to the kind of open science envisioned by the report, such as cost barriers to widespread implementation of open publication and data, as well as a culture and incentive system that does not adequately reward open science practices and may even discourage then.

To help overcome these barriers and advance open science, the report recommends the following:

- Research institutions should work to create a culture that actively supports Open Science by Design by better rewarding and supporting researchers engaged in open science practices.
- Research institutions and professional societies should train students and other researchers to implement open science practices effectively.
- Research funders and research institutions should develop policies and procedures to identify the data, code, specimens, and other research products that should be preserved for long-term public availability, and they should provide the resources necessary for the long-term preservation and stewardship of those research products.
- Funders that support the development of research archives should work to ensure that these are designed and implemented according to the FAIR (Findable, Accessible, Interoperable, Reusable) data principles. Researchers should seek to ensure that their research products are made available according to the FAIR principles.

Overall, the report urges the research community to work together to realize its vision of Open Science by Design in order to advance science and to help science better serve the needs of society.

Open Science by Design can be downloaded free of charge at https://www.nap.edu/catalog/25116.



FOSTERING INTEGRITY IN RESEARCH

As part of its examination of how to support integrity in scientific research, this report affirms the values of openness and transparency and their value in supporting reproducibility and replicability.

In many fields and disciplines, the report says, current standards for transparency are not adequately supporting reproducibility and replicability. While the research enterprise has begun to take important steps—for example, many universities and funding agencies have created online repositories to disseminate digital data—current data practices vary significantly by field and discipline, and barriers to progress remain. Preparing data and code for release can be expensive and time consuming; while researchers are currently rewarded for manuscript publication, the professional rewards for preparing data and code for publication are minimal, and the resources to support the endeavor are often limited as well.

Among the report's recommendations are some targeted at improving transparency and openness in reporting on studies, with the goal of making it easier to reproduce and replicate research:

- Research sponsors and publishers should ensure that information sufficient to replicate reported results is made available at the time of publication or as soon as possible after publication.
- Federal funding agencies and other research sponsors should allocate sufficient funds to enable the long-term storage, archiving, and access of datasets and code necessary to reproduce and replicate published findings.
- To avoid unproductive duplication of research and to permit effective judgments on the statistical significance of findings, researchers should routinely disclose all statistical tests carried out, including negative findings.

The report also urges journals to update their publication requirements to include access to data and code needed to reproduce results in the manuscript. To facilitate the reuse of scientific code and data, these objects should be shared in ways that maximize access while respecting scientific norms such as attribution.

Fostering Integrity in Research can be downloaded free of charge at https://www.nap.edu/catalog/21896.

To see the National Academies' body of work on scientific reproducibility, visit https://www.nap.edu/collection/89/reproducibility.

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