complements efforts of the research enterprise and its key stakeholders.

Universities should insist that their faculties and students are schooled in the ethics of research, their publications feature neither honorific nor ghost authors, their public information offices avoid hype in publicizing findings, and suspect research is promptly and thoroughly investigated. All researchers need to realize that the best scientific practice is produced when, like Darwin, they persistently search for flaws in their arguments. Because inherent variability in biological systems makes it possible for researchers to explore different sets of conditions until the expected (and rewarded) result is obtained, the need for vigilant self-critique may be especially great in research with direct application to human disease. We encourage each branch of science to invest in case studies identifying what went wrong in a selected subset of nonreproducible publications—enlisting social scientists and experts in the respective fields to interview those who were involved (and perhaps examining lab notebooks or redoing statistical analyses), with the hope of deriving general principles for improving science in each field.

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Industry should publish its failed efforts to reproduce scientific findings and join scientists in the academy in making the case for the importance of scientific work. Scientific associations should continue to communicate science as a way of knowing, and educate their members in ways to more effectively communicate key scientific findings to broader publics. Journals should continue to ask for higher standards of transparency and reproducibility.

We recognize that incentives can backfire. Still, because those such as enhanced social image and forms of public recognition (*10*, *11*) can increase productive social behavior (*12*), we believe that replacing the stigma of retraction with language that lauds reporting of unintended errors in a publication will increase that behavior. Because sustaining a good reputation can incentivize cooperative behavior (*13*), we anticipate that our proposed changes in the review process will not only increase the quality of the final product but also expose efforts to sabotage independent review. To ensure that such incentives not only advance our objectives but above all do no harm, we urge that each be scrutinized and evaluated before being broadly implemented.

Will past be prologue? If science is to enhance its capacities to improve our understanding of ourselves and our world, protect the hard-earned trust and esteem in which society holds it, and preserve its role as a driver of our economy, scientists must safeguard its rigor and reliability in the face of challenges posed by a research ecosystem that is evolving in dramatic and sometimes unsettling ways. To do this, the scientific research community needs to be involved in an ongoing dialogue. We hope that this essay and the report *The Integrity of Science* (*14*), forthcoming in 2015, will serve as catalysts for such a dialogue.

Asked at the close of the U.S. Constitutional Convention of 1787 whether the deliberations had produced a republic or a monarchy, Benjamin Franklin said "A Republic, if you can keep it." Just as preserving a system of government requires ongoing dedication and vigilance, so too does protecting the integrity of science. ■

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SCIENTIFIC STANDARDS

Promoting an open research culture

Author guidelines for journals could help to promote transparency, openness, and reproducibility

By **B. A. Nosek,* G. Alter, G. C. Banks, D. Borsboom, S. D. Bowman, S. J. Breckler, S. Buck, C. D. Chambers, G. Chin, G. Christensen, M. Contestabile, A. Dafoe, E. Eich, J. Freese, R. Glennerster, D. Goroff, D. P. Green, B. Hesse, M. Humphreys, J. Ishiyama, D. Karlan, A. Kraut, A. Lupia, P. Mabry, T. A. Madon, N. Malhotra, E. Mayo-Wilson, M. McNutt, E. Miguel, E. Levy Paluck, U. Simonsohn, C. Soderberg, B. A. Spellman, J. Turitto, G. VandenBos, S. Vazire, E. J. Wagenmakers, R. Wilson, T. Yarkoni**

Transparency, openness, and reproducibility are readily recognized as vital features of science (*1*, *2*). When asked, most scientists embrace these features as disciplinary norms and values (*3*). Therefore, one might expect that these valued features would be routine in daily practice. Yet, a growing body of evidence suggests that this is not the case (*4*–*6*).

A likely culprit for this disconnect is an academic reward system that does not sufficiently incentivize open practices (*7*). In the present reward system, emphasis on innovation may undermine practices that support verification. Too often, publication requirements (whether actual or perceived) fail to encourage transparent, open, and reproducible science (*2*, *4*, *8*, *9*). For example, in a transparent science, both null results and statistically significant results are made available and help others more accurately assess the evidence base for a phenomenon. In the present culture, however, null results are published less frequently than statistically significant results (*10*) and are, therefore, more likely inaccessible and lost in the "file drawer" (*11*).

The situation is a classic collective action problem. Many individual researchers lack strong incentives to be more transparent, even though the credibility of science would benefit if everyone were more transparent. Unfortunately, there is no centralized means of aligning individual and communal incentives via universal scientific policies and procedures. Universities, granting agencies, and publishers each create different incentives for researchers. With all of this complexity, nudging scientific practices toward greater openness requires complementary and coordinated efforts from all stakeholders.

THE TRANSPARENCY AND OPENNESS PROMOTION GUIDELINES. The Transparency and Openness Promotion (TOP) Committee met at the Center for Open Science in Charlottesville, Virginia, in November 2014 to address one important element of the incentive systems: journals' procedures and policies for publication. The committee consisted of disciplinary leaders, journal editors, funding agency representatives, and disciplinary experts largely from the social and behavioral sciences. By developing shared standards for open practices across journals, we hope to translate scientific norms and values into concrete actions and change the current incentive structures to drive researchers' behavior toward more openness. Although there are some idiosyncratic issues by discipline, we sought to produce guidelines that focus on the commonalities across disciplines.

*Standards***.** There are eight standards in the TOP guidelines; each moves scientific communication toward greater openness. These standards are modular, facilitating adoption in whole or in part. However, they also complement each other, in that commitment to one standard may facilitate adoption of others. Moreover, the guidelines are sensitive to barriers to openness by articulating, for example, a process for exceptions to sharing because of ethical issues, intellectual property concerns, or availability of necessary resources. The complete guidelines are available in the TOP information commons at http://cos.io/top, along with a list of signatories that numbered 46 journals and 11 organizations as of 28 May 2015. The table provides a summary of the guidelines.

ILLUSTRATION: DAVIDE BONAZZI

First, two standards reward researchers for the time and effort they have spent engaging in open practices. (i) Citation standards extend current article citation norms to data, code, and research materials. Regular and rigorous citation of these materials credit them as original intellectual contributions. (ii) Replication standards recognize the value of replication for independent verification of research results and identify the conditions under which replication studies will be published in the journal. To progress, science needs both innovation and self-correction; replication offers opportunities for self-correction to more efficiently identify promising research directions.

Second, four standards describe what openness means across the scientific process so that research can be reproduced and evaluated. Reproducibility increases confidence in results and also allows scholars to learn more about what results do and do not mean. (i) Design standards increase transparency about the research process and reduce vague or incomplete reporting of the methodology. (ii) Research materials standards encourage the provision of all elements of that methodology. (iii) Data sharing standards incentivize authors to make data available in trusted repositories such as Dataverse, Dryad, the Interuniversity Consortium for Political and Social Research (ICPSR), the Open Science Framework, or the Qualitative Data Repository. (iv) Analytic methods standards do the same for the code comprising the statistical models or simulations conducted for the research. Many discipline-specific standards for disclosure exist, particularly for clinical trials and health research more generally (e.g., www.equator-network.org). Many more are emerging for other disciplines, such as those developed by *Psychological Science* (*12*).

Finally, two standards address the values resulting from pre-registration. (i) Standards for preregistration of studies facilitate the discovery of research, even unpublished research, by ensuring that the existence of the study is recorded in a public registry. (ii) Preregistration of analysis plans certify the distinction between confirmatory and exploratory research, or what is also called hypothesis-testing versus hypothesis-generating research. Making transparent the distinction between confirmatory and exploratory methods can enhance reproducibility (*3*, *13*, *14*).

*Levels***.** The TOP Committee recognized that not all of the standards are applicable to all journals or all disciplines. Therefore, rather than advocating for a single set of guidelines, the TOP Committee defined

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three levels for each standard. Level 1 is designed to have little to no barrier to adoption while also offering an incentive for openness. For example, under the analytic methods (code) sharing standard, authors must state in the text whether and where code is available. Level 2 has stronger expectations for authors but usually avoids adding resource costs to editors or publishers that adopt the standard. In Level 2, journals would require code to be deposited in a trusted repository and check that the link appears in the article and resolves to the correct location. Level 3 is the strongest standard but also may present some barriers to implementation for some journals. For example, the journals *Political Analysis* and *Quarterly Journal of Political Science* require authors to provide their code for review, and editors reproduce the reported analyses publication. In the table, we provide comparison of common journal policies that do not meet the transparency standards.

Adoption. Defining multiple levels and distinct standards facilitates informed decision-making by journals. It also acknowledges the variation in evolving norms about research transparency. Depending on the discipline or publishing format, some of the standards may not be relevant for a journal. Journal and publisher decisions can be based on many factors–including their readiness to adopt modest to stronger transparency standards for authors, internal journal operations, and disciplinary norms and expectations. For example, in economics, many highly visible journals such as *American Economic Review* have already adopted strong policies requiring data sharing, whereas few psychology journals have comparable requirements.

In this way, the levels are designed to facilitate the gradual adoption of best practices. Journals may begin with a standard that rewards adherence, perhaps as a step toward requiring the practice. For example, *Psychological Science* awards badges for "open data," "open materials," and "preregistration" (*12*), and approximately 25% of accepted articles earned at least one badge in the first year of operation.

The Level 1 guidelines are designed to have minimal effect on journal efficiency and workflow while also having a measurable impact on transparency. Moreover, although higher levels may require greater implementation effort up front, such efforts may benefit publishers and editors and the quality of publications by, for example, re-

Headline TKTK

Explainer text TKTK

	LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3
Citation standards	Journal encourages citation of data, code, and materials–or says nothing.	Journal describes citation of data in guidelines to authors with clear rules and examples.	Article provides appropriate citation for data and materials used, consistent with journal's author guidelines.	Article is not published until appropriate citation for data and materials is provided that follows journal's author guidelines.
Data transparency	Journal encourages data sharing–or says nothing.	Article states whether data are available and, if so, where to access them.	Data must be posted to a trusted repository. Exceptions must be identified at article submission.	Data must be posted to a trusted repository, and reported analyses will be reproduced independently before publication.
Analytic methods (code) transparency	Journal encourages code sharing–or says nothing.	Article states whether code is available and, if so, where to access them.	Code must be posted to a trusted repository. Exceptions must be identified at article submission.	Code must be posted to a trusted repository, and reported analyses will be reproduced independently before publication.
Research materials transparency	Journal encourages materials sharing–or says nothing	Article states whether materials are available and, if so, where to access them.	Materials must be posted to a trusted repository. Exceptions must be identified at article submission.	Materials must be posted to a trusted repository, and reported analyses will be reproduced independently before publication.
Design and analysis transparency	Journal encourages design and analysis transparency or says nothing.	Journal articulates design transparency standards.	Journal requires adherence to design transparency standards for review and publication.	Journal requires and enforces adherence to design transparency standards for review and publication
Preregistration of studies	Journal says nothing.	Journal encourages preregistration of studies and provides link in article to preregistration if it exists.	Journal encourages preregistration of studies and provides link in article and certification of meeting preregistration badge requirements.	Journal requires preregistration of studies and provides link and badge in article to meeting requirements.
Preregistration of analysis plans	Journal says nothing.	Journal encourages preanalysis plans and provides link in article to registered analysis plan if it exists.	Journal encourages preanalysis plans and provides link in article and certification of meeting registered analysis plan badge requirements.	Journal requires preregistration of studies with analysis plans and provides link and badge in article to meeting requirements.
Replication	Journal discourages submission of replication studies–or says nothing.	Journal encourages submission of replication studies.	Journal encourages submission of replication studies and conducts blind review of results.	Journal uses Registered Reports as a submission option for replication studies with peer review before observing the study outcomes.

ducing time spent on communication with authors and reviewers, improving standards of reporting, increasing detectability of errors before publication, and ensuring that publication-related data are accessible for a long time.

Evaluation and revision. An information commons and support team at the Center for Open Science is available (top@cos.io) to assist journals in selection and adoption of standards and will track adoption across journals. Moreover, adopting journals may suggest revisions that improve the guidelines or make them more flexible or adaptable for the needs of particular subdisciplines.

The present version of the guidelines is not the last word on standards for openness in science. As with any research enterprise, the available empirical evidence will expand with application and use of these guidelines. To reflect this evolutionary process, the guidelines are accompanied by a version number and will be improved as experience with them accumulates.

Conclusion. The journal article is central to the research communication process. Guidelines for authors define what aspects of the research process should be made available to the community to evaluate, critique, reuse, and extend. Scientists recognize the value of transparency, openness, and reproducibility. Improvement of journal policies can help those values become more evident in daily practice and ultimately improve the public trust in science, and science itself. ■

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SUPPLEMENTARY MATERIALS

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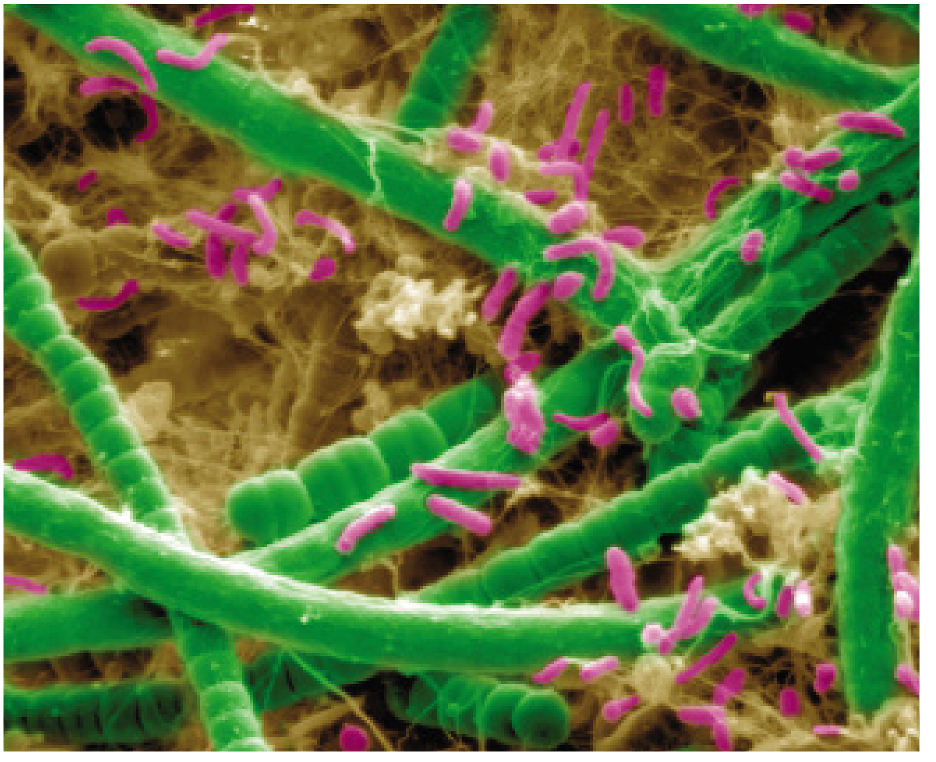

Learning from nature. Photomicrograph of cyanobacterial-heterotroph microbial consortia derived from a phototrophic microbial mat community from a saline lake. Emerging understanding of cooperative mechanisms in such communities may be helpful in the design of synthetic communities for use in biotechnology.

ECOLOGY

Ecological communities by design

Synthetic ecology requires knowledge of how microbial communities function

By **James K. Fredrickson**

In synthetic ecology, a nascent offshoot of synthetic biology, scientists aim to design and construct microbial communities with desirable properties. Such mixed populations of microorganisms can simultaneously perform otherwise incompatible functions (*1*). Compared with individual organisms, they can also better resist losses in function as a result of environmental perturbation or invasion by other species (*2*). Synthetic ecology may thus be a promising approach for developing robust, stable biotechnological processes, such as the conversion of cellulosic biomass to biofuels (*3*). However, achieving this will require detailed knowledge of the principles that guide the structure and function of microbial communities (see the image).

Recent work with synthetic communities is shedding light on microbial interactions that may lead to new principles for community design and engineering. In game theory, cooperators provide publicly available goods that benefit all, whereas cheaters exploit those goods without reciprocation. The tragedy of the commons predicts that cheaters are more fit than cooperators, eventually destroying the cooperation. Yet, this is not borne out by observations. For example, using a synthetic consortium of genetically modified yeast to represent cooperators and cheaters, Waite and Shou (*4*) found that, although initially less fit than cheaters, cooperators rapidly dominated in a fraction of the cultures. The evolved cooperators harbored mutations allowing them to grow at much lower nutrient concentrations than their ancestor. This suggests that the tragedy of the commons can be avoided