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Reproducing synthesis

Irreproducible synthetic methods consume time, money, and resources. Here, we highlight the steps *Nature Synthesis* takes to help authors make their synthetic procedures as reproducible as possible.

Attempting to reproduce irreproducible or unreliable synthetic methods can waste time, money, and resources. Irreproducibility in synthesis is not just limited to unobserved reactivity, it can present itself in many forms including variations in reaction yields or selectivity in an organic transformation or inconsistent catalytic performance of a newly developed material (*Angew. Chem. Int. Ed.* **55,** 12548–12549; 2016). There are numerous causes of irreproducibility and unreliability in synthetic methods, ranging from small details unbeknown to researchers at the time of development, for example the presence of reagent impurities, to fabrication of results and data. Another source of irreproducibility is the assumption of knowledge in a synthetic procedure, making it challenging for researchers from other disciplines or who are new to the community to reproduce procedures.

Although the tribulations experienced in trying to reproduce irreproducible synthetic procedures may lead chemists and materials scientists to discover something unexpected or develop improved routes to target molecules and materials, reported synthetic methods should be able to be safely and efficiently replicated in laboratories and manufacturing plants globally, without the need for process-specific knowledge or experience.

In an ideal world, all synthetic procedures would be rigorously tested and reproduced by other members of the community prior to being reported, however given the ever-growing quantity of synthetic procedures being developed, this is simply not possible. As such, high-quality and detailed reporting of procedures, product characterization data and methods, reaction setup and equipment descriptions, as well as material source and specification information are vital to enable members of the synthetic community to readily replicate a new synthetic method.

An additional strategy for improving the reproducibility of synthetic procedures could be to establish a standardized approach to procedure reporting across the synthesis community. In an Article in this issue, Hein, Cronin and co-workers report the use of a universal chemical programming language (χDL) to encode and perform synthetic processes across three automated platforms at the University of British Columbia and the University of Glasgow. χDL is a human- and machine-readable language that standardizes synthetic procedures and enables them to be performed by automated synthesis platforms. Hein, Cronin and co-workers demonstrate that χDL synthetic procedures can be readily shared and validated between automated synthesis platforms, in host-to-peer or peer-to-peer transfers, akin to BitTorrent data file sharing. The concept is demonstrated through three case studies, using a range of organic reactions, across three different automated synthesis platforms. Canty and Jensen further discuss the concept of using χDL to reproducibly transfer procedures between automated synthesis platforms in a News & Views featured in this issue.

It remains to be seen if the synthetic community will widely adopt a standardized method for reporting and sharing reproducible synthetic procedures in the way that χDL can be used for automated procedures. In the meantime, at *Nature Synthesis* we ask our authors and reviewers to follow a range of mandates and suggestions to ensure the synthetic procedures we publish are as reliable and reproducible as possible. The following sections provide an insight into some of the information and data we ask authors to provide when publishing a Research Article with *Nature Synthesis* which help others to reproduce the work.

Methods. Research Articles feature a Methods section in the main text of the article. This section provides general synthetic procedures that are representative of the processes developed within the article. Any further method details that are required to reproduce the research reported should be provided in the Supplementary Information. These may include detailed descriptions of experimental setups, instrumentation for characterization, reagent and material specifications, computational procedures, and step-by-step protocols to synthesize compounds and materials.

Data availability. It is mandatory for Articles to include a data availability statement describing the availability of all data that supports the reported research. Our guidance encourages authors to make relevant data readily available to our readers. We ask authors that, where possible, data are not only "available on request". In cases where data are only available on request, we ask authors to state which data this refers to and to provide reasoning as to why these data are only available on request.

Following editorial assessment, if an Article is to be sent for peer review, we ask authors to complete an Editorial Policy Checklist, and, if applicable, specialist checklists such as a Life Sciences Reporting Summary, Code and Software Submission Checklist, or Solar Cells Reporting Summary. Developed by the Nature Portfolio, these checklists help authors enhance the reproducibility of their work by ensuring data are suitably presented and are available for reviewer assessment, and, if accepted, for the reader. These checklists ensure data availability and reporting are consistent across Articles and field-specific data are reported and presented in accordance with our policies and the expectations of the research area.

We encourage authors, where necessary, to provide source data for all figures and extended data figures presented, which are available with the Article. For data that are specific to a particular technique, for example, X-ray crystallography, these data should be deposited at the appropriate database, such as the Cambridge Crystallographic Data Centre or the Protein Data Bank, and required files should be provided at submission of the Article, for assessment by editors and reviewers, as per our guidelines.

If an Article features previously unpublished code or software that is central to the work, we ask authors to adhere to the Nature Portfolio code and software guidelines at submission of the Article. Upon publication of the Article, we ask authors to release the associated version of the code or software and deposit it at a DOI-minting repository.

Authors are also encouraged to manage subsequent versions of the code or software.

We also encourage authors to share non-specialist raw data files through data repositories, such as Figshare. Access to these files should be provided from the initial submission of an Article to allow reviewers and editors to assess the completeness and appropriateness of any data deposition.

Characterization. Articles should contain sufficient characterization data to support the claims made in the Article and confirm the identity and purity of molecules and materials produced. For example, if spectroscopic analyses, such as ^{1}H, $^{13}C\{^{1}H\}$, or heteronuclear NMR spectroscopy, are used in the confirmation of the chemical identity of a small organic molecule, then peak listings, the solvent used, spectra, and spectrometer specifications should be provided. If feasible, raw data files for all characterization methods should be provided in any data repository submissions, ideally in non-proprietary formats, to enable others to compare with their own characterization data when reproducing a synthetic procedure.

As the field of synthesis evolves, we will continue to review our editorial guidance to continue to help authors communicate detailed synthetic procedures so that the chemistry and materials science communities can readily reproduce synthetic work reported in *Nature Synthesis*.

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