

Reproducibility by Other Means: Transparent Research Objects with Science-Oriented Provenance

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1 ABSTRACT

2 INTRODUCTION

Reproducibility in science.

Modern science is founded on the expectation that the observations, experiments, and predictions that comprise scientific research be independently verifiable by others. This requirement, referred to as the *reproducibility* of science, applies not only to the products of research studies (*results, conclusions, models, data products, predictions*), but also to the activities comprising a study that ultimately give rise to these products (*methods, protocols, workflows*); the materials employed in these research activities (*reagents, instruments, software*); and the conditions under which these activities are carried out (*instrument settings, software parameters, computing environments*). When sufficient details are available such that the research products and methods can be reviewed, interpreted, and evaluated by other researchers *without* repeating the work, a study is said to be *transparent*.

While it is true that studies attempting primarily to reproduce previous results are relatively rare in the natural sciences, even the most groundbreaking studies in these fields include components that explicitly or implicitly confirm the reproducibility of previous results and reported procedures. The expectation is that new studies will reliably produce meaningful results consistent with previous work only if the prior work on which it is based or relates to is reproducible. In this sense, the whole of basic research in the natural sciences can be seen as an ongoing, massively-parallel reproducibility study that also happens to produce new results. Exceptions to this pattern occur when studies appear to overturn well-established understandings of nature, violate the expectations of how research in a particular field is to be carried out, or otherwise cause controversy. In these cases direct attempt may be made to reproduce results by precisely replicating the reported methods and conditions reported in the controversial study.

Limits on exact repeatability.

Even when attempts are made to confirm the reproducibility of particular studies or results, investigators in the natural sciences generally do not expect the products of research to be repeated exactly. The vast majority of quantitative observations made of real world phenomena using scientific instruments are associated with limited precision and other intrinsic uncertainties that must themselves be characterized and well understood for science based on them to be considered reproducible (no error bars on graph => not reproducible). It is a hallmark of trustworthy science that quantitative observations and claims be inseparable from the uncertainty in the reported values ultimately deriving from these uncertainties in measurement and the resulting propagation of errors through data analysis.

In contrast, digital computing approaches make it possible to repeat *exactly* certain computational aspects of research to an extent that far exceeds what can be achieved when observing natural phenomena in the physical world. It generally is expected that computational processes, the implementation of hardware and software enabling those processes, and the outputs of those processes all can be repeated exactly—at least in principle. Where computing makes up a significant fraction of scientific research, there is a risk that the longstanding understanding of reproducibility in the sciences can be conflated with this new, radically different expectation of exact repeatability.

Moreover, while exact repeatability of computational experiments and analyses may be realizable in principle, in practice the complexities of real-world hardware and software make computational repeatability very challenging to achieve in practice except in very limited cases. Currently much effort is going into expanding the fraction of scenarios in which the computational components of research can be automatically repeated exactly over ranges of time and space relevant to scientific research and discourse. These efforts are important for the research community to pursue, and for science funding agencies to support, especially because the computing industry generally does not have requirements for exact repeatability across significant spans of time. However, it also is crucial to note that the concept of exact repeatability of the kind pursued by these efforts is qualitatively different from the concept of reproducibility that underlies the natural sciences. It is even more important to realize that scientific reproducibility is not simply a weaker form of computational repeatability. Achieving computational repeatability does not automatically deliver scientific reproducibility.

Reproducibility by other means.

It is both bad and good news that exact, computational repeatability is not tantamount to reproducibility. The bad news is that it is possible to put much effort into achieving computational repeatability without delivering the kind of reproducibility that is critical for producing trustworthy science. The good news is that scientifically-meaningful reproducibility can be realized in cases (or over spans of time) where computational repeatability is either impossible or impractical given the limitations of readily available technology and affordable resources. In this paper we propose that the older concept of reproducibility that permeates the natural sciences has a very useful role even where digital computing makes exact repeatability a theoretical possibility.

Researchers in the natural sciences are comfortable with the idea that it is not possible to exactly repeat all reported observations, procedures, and experimental results. They do not see this concession to real-world practicalities as a contradiction to their demand that science be reproducible. What the natural sciences actually do demand is that (a) research procedures be repeatable by others in

principle. (b) The means of repeating the work be subject to review and evaluation. (c) Such review and evaluation be possible without actually repeating the work. To be clear, in the natural sciences it is actually considered a *problem* if exact repetition of the steps taken in reported research is required either to evaluate the work or to reproduce results.

The reason this is good news for computation-intensive research is that it is not necessary to achieve or maintain perfect repeatability of the computational components of research in order for scientists to consider the work reproducible and therefore trustworthy. However, this also means that it is critical that the standards, technologies, and computational best-practices that we develop and advocate in fact support scientific reproducibility. Pursuing and supporting exact computational repeatability is not enough. Indeed, as we will show below, computational repeatability can be thought of as a dimension of research reproducibility *orthogonal* to transparency. Consequently, it is possible to achieve computational repeatability without providing research transparency—and vice versa. And while exact repeatability is not an essential element of reproducibility, transparency is.

Research Objects for research transparency.

In this paper we argue that the dimension of reproducible research most at risk of neglect when supporting computational repeatability is transparency. It is well established that that an area in which computer science has much to offer in supporting transparency is in the modeling, recording, and querying of the provenance of research artifacts. What we emphasize here is that for provenance to support reproducibility it must support science-oriented queries. Provenance must be able to answer questions about the *science* that was performed—not just the sequence, dependencies, and flow of data through computational steps. The answers to these questions must enable others to evaluate the scientific quality of the work, and to learn what is necessary to reproduce the results without blindly repeating every step taken in the original work, and to build on the work with confidence. And it must be possible for researchers unversed in the detailed metadata specifications of Research Objects and the PROV standard, to pose these questions and receive answers meaningful for evaluating, using, and building on the processes and products of prior research. We suggest that Research Objects and related approaches are the ideal vehicle for storing and make provenance queryable in this way. Research Objects thus can support scientific reproducibility even in the face of the many practical challenges to exact computational repeatability.

3 TERMINOLOGY

Recent years have seen a growing debate over the meanings of the terms reproducible and replicable, and relationships between the two. Should one term imply a greater adherence to the procedures taken in the original research? Should one term be reserved for the activities a researcher performs to assess the reliability of their own procedures, experiments, and results; leaving the other term to refer to activities centered on assessing the quality of the results of others? Which term should be used to mean what? As alluded to in the introduction, the entry of digital computing into scientific research has further complicated these issues by introducing the

possibility of exact repeatability. For the purposes of this paper we will continue to reserve the terms reproducibility and replicability to qualities demanded of scientific research whether digital computers are involved or not. We use the term repeatability to refer to quality of computations that is desirable so far as computers are involved in research, but do not consider repeatability in this sense to be a prerequisite of reproducibility or replicability even when computers are used in research. For the relative meanings of reproducibility and replicability, we follow here the recommendations of the Federation of American Societies for Experimental Biology, an organization comprising twenty-nine scientific societies and representing over 105,000 practicing researchers:

Replicability: the ability to duplicate (i.e., repeat) a prior result using the same source materials and methodologies. This term should only be used when referring to repeating the results of a specific experiment rather than an entire study.

Reproducibility: the ability to achieve similar or nearly identical results using comparable materials and methodologies. This term may be used when specific findings from a study are obtained by an independent group of researchers

Note that by these definitions replicating a result implies following the processes reported in the original work more closely ("same source materials and methodologies"), than when reproducing a result ("comparable materials and methodologies"). Neither definition refers specifically to computed results and both apply to experimental results. In contrast, the recent report from the National Academy of Sciences reverses the relative fidelity implied by the terms 'reproducibility' and 'replicability':

Reproducibility is obtaining consistent results using the same input data, computational steps, methods, and code, and conditions of analysis.

Replicability is obtaining consistent results across studies aimed at answering the same scientific question, each of which has obtained its own data.

Perhaps most intriguing about the NAS definitions is that experiments not carried out entirely in silico apparently are left with only term to describe them: replicability. Satisfying the definition of reproducibility requires "computational steps" and "code", and the report goes on to clarify that reproducibility "is synonymous with 'computational reproducibility,' and the terms are used interchangeably in this report."

FASEB also defines transparency in a manner consistent with our usage here:

Transparency: the reporting of experimental materials and methods in a manner that provides enough information for others to independently assess and/or reproduce experimental findings

In contrast, the NAS report essentially makes reproducibility a prerequisite of transparency: "When a researcher transparently reports a study and makes available the underlying digital artifacts, such as data and code, the results should be computationally reproducible."

We take the position that it transparency is essential to science, whereas reproducibility as defined by the NAS is not necessarily possible, as detailed below.

Footnote or note at end of paper:

Cell and molecular biologists study both replication and reproduction as natural processes. DNA replicates : high fidelity, variation

not desired, ingredients indistinguishable, errors are corrected on the fly. Organisms reproduce: lower fidelity expected, variation desired, different ingredients acceptable. Cells have replisomes, complex molecular machines where DNA replication occurs, and copying errors are detected and corrected. In origin of life research a crucial debate is over 'replication first' (DNA World) or 'metabolism first' (aka reproduction first, i.e. without replicating genetic material). These terminologies with biology are well established. Biologists also have a rich and well-defined vocabulary to describe replicability of experimental measurements and results. Commonly distinguish two kinds of experimental 'replicates': technical replicates, and biological replicates. Reality is that the terminology is well established in large branches of science already.

Need for reproduction/replication to mean different things in different fields

The relationships of corresponding concepts across fields is one of analogy, not identity. Exact repeatability is at least theoretically possible and sometimes practical under realistic assumptions when an experiment is entirely *in silico* and isolated from the outside world. As soon as observation of the real world is involved, exact repeatability often is impossible. Neither of the types of replicates in experimental biology are exact, although both are measures of repeatability. There often is no way to repeat exactly an experiment that involves scientific instruments, physical samples, or experimental apparatus. In contrast, it is not unreasonable to talk about exactly repeating a purely computational experiment, at least by the original researcher, on the same hardware, close in time to the original experiment. In reality, computational repeatability is not as easy as sometimes assumed (see below), but fundamentally this is a different situation than when a scientific instrument is involved or observations are made of the external world.

Our approach to terminology

Respect differences between fields of research and different expectations with regard to reproducibility. Do not expect standardization to even be meaningful (never mind politically achievable) across domains. Instead, only use the R* words in ways that make their meanings clear in context. Do not be surprised if computational sciences turn out not to be representative of science generally.

Specific implications for our contributions to the Research Objects field

Take care to define R* words precisely when expressing desiderata, describing features, or making or comparing claims about capabilities. Do not expect efforts to achieve computational repeatability alone to enable "reproducible science" generally.

4 COMPUTATIONAL CHALLENGES

The fundamental limitations computers impose on replicability of program executions are well known.

Finite precision arithmetic, different word sizes on different processors, round-off errors, etc, impose limits on scientific computations and their replicability across different computing environments. Virtual machines and containers do not address these issues. Full emulation is required to run the same binary in identical fashion on a different processor. This is typically slow. These limitations are even more challenging to manage reproducibly because programs typically are compiled, meaning that the exact sequence of

machine instructions executed even by a single processor cannot generally be controlled. A different compiler, or a newer version of the same compiler will yield a different sequence of machine instructions.

Replicating the outputs of a program is far from straightforward

Observing that a program or set of programs can be executed again is not sufficient to conclude that the underlying computation was replicated. The outputs of the programs must be checked for equivalence. Because of the expected variation in run time behavior of programs due to the issues above, checking that outputs of a program run are equivalent to the outputs of a run of that program is not always as simple as comparing the outputs for bitwise identity. Robustly checking for equivalence of output generally must be confirmed in some way other than comparing files at the bit level. Footnote: The excellent practice of including accurate provenance and other meaningful metadata in data file headers makes it even more unlikely that outputs from different runs will be bitwise-identical.

Replicating just the software running the program is challenging in practice

How can we ensure that the stream of instructions sent to the processor for two executions is identical? Even holding the computer hardware and compiler version constant, programs depend on language libraries, OS libraries, and system calls. Much scientific software also depends directly and indirectly on large numbers of 3rd-party libraries. Only direct dependencies can be controlled reliably at build-time. And many dependencies are via shared libraries that can change between executions of the exact same executable—no recompile is needed to get a new effective executable. Footnote: Fans of the Go programming language are bringing back the static executable. Recompiling or even just rerunning the "same" program a week later can result in a completely different effective instruction stream.

Even reproducing computing environments is hard

Containers and their discontents Footnote: By 'discontents' we do not mean that we object to the use of containers, but rather than we are not content with container technology alone. There currently is much enthusiasm around containers as a means of reproducing computing environments and making computational science replicable. Whole Tale is one of several projects leveraging the capabilities of containers for this purpose. Others include Binder and Code Ocean. In Whole Tale it is recognized that containers alone cannot satisfy researcher's needs for sharing their computing environments and computations. Rather, container technology such as Docker provide an invaluable tool for the reproducible science software stack architect. A major motivation for funding (and continuing to fund) projects like Whole Tale is that the containers on their own are insufficient as means to making computational science reproducible, and it is not practical for individual researchers and groups to use containers and other technology to actually achieve scientifically meaningful reproducibility over periods longer than the publication-cycle time scale.

What containers do not do Despite what sound like suggestions to the contrary in the literature, container technology such as Docker do not ensure computational replicability, and do not on their own solve any of the problems of computational replicability described above. What containers do provide a very convenient

means for executing customized computing environments on behalf of researchers, without having to run an entire virtual machine for each environment. In common with virtual machine technology, containers do not abstract or hide the underlying hardware architecture of the computer on which they run. They do not abstract the underlying operating system, but simply use the Linux kernel on the host. Kernel parameter settings on the host apply to all containers running on the host (reference famous blog post on the topic "Containers Do Not Contain"). Rebuilding an image from its Dockerfile specification is not guaranteed to yield the same image. In general it will not. Container images, once they are built, are not guaranteed to run on future releases of the container host. They also do not ensure that computations run within the container will be replicable in the future.

What containers are good for is precisely what they were to do for the computing industry: enable developers to write and test code in a computing environment of a developer's choosing that can then be replicated on a very short time scale (hours or days) in staging and production environments. Containers also are good at managing conflicts in dependencies between different components of a multiprocess software architecture. Using containers to 'contain' dependencies in this way is most effective when an application can be split across multiple containers running in concert. The model of one container, one computing environment does not lend itself to dependency isolation.

The problem of time and dependencies An emerging threat to reproducibility of computational science is the spread misconception that sharing the definition of a container image, e.g. by including a Dockerfile in the Git repo for the project, is a guarantee that others (or even the original researcher) will be able to recreate the corresponding image and computing environment it represents. Researchers making this assumption may be less likely to preserve all of the information actually required to reproduce their computations. A major reason a Dockerfile is not enough is that the implicit dependencies of the built environment are constantly changing. This is well known to anyone working directly with Docker, or other container technologies. Here we will give a single example of the implications of this issue for reproducible science.

What is reproducibility really for?

Achieving meaningful replicability even for the computational parts of research is very challenging. But this is no reason to give up hope. Replicability is a means to an end—justification of scientific results—and Research Objects can help us achieve that end by other means. What is most exciting about Research Objects is that they can achieve this end despite the difficulty of computational replicability. And the primary means by which Research Objects can do this is by providing transparency.

REFERENCES