To be FAIR: Theory Specification Needs an Update

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Abstract

Innovations in open science and meta-science have focused on rigorous *theory testing*, yet methods for specifying, sharing, and iteratively improving theories remain underdeveloped. To address these limitations, we introduce *FAIR theory*: A standard for specifying theories as Findable, Accessible, Interoperable, and Reusable information artifacts. FAIR theories are Findable in well-established archives, Accessible in practical terms (open file formats) and in terms of their ability to be understood, Interoperable for specific purposes, e.g., to guide control variable selection, and Reusable such that they can be iteratively improved. This paper adapts the FAIR priciples for theory, reflects on the FAIRness of contemporary theoretical practices in psychology, introduces a workflow for FAIRifying theory, and explores FAIR theories' potential impact in terms of reducing research waste, enabling meta-research on the structure and development of theories, and incorporating theory into reproducible research workflows – from hypothesis generation to simulation studies. We make use of well-established open science infrastructure, including Git for version control, GitHub for collaboration, and Zenodo for archival and search indexing. By applying the principles and infrastructure that have already revolutionized sharing of data and publications to theory, we establish a sustainable, transparent, and collaborative approach to theory development. FAIR theory equips scholars with a standard for systematically specifying and refining theories, bridging a critical gap in open research practices and supporting the renewed interest in theory development in psychology and beyond. FAIR theory provides a structured, cumulative framework for theory development, increasing efficiency and potentially accelerating the pace of cumulative knowledge acquisition.

Keywords: fairtheory, meta theory, theory formation, cumulative science, formal models

Word count: 8881

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The FAIR Guiding Principles (hereafter: FAIR principles) were established to improve the reusability of research data by making them more Findable, Accessible, Interoperable and Reusable (M. D. Wilkinson et al., 2016a) for both humans and computers. Since the FAIR principles' inception, scholars have demonstrated their relevance for making other information artifacts more open, such as research software (Lamprecht et al., 2019) and computational workflows (S. R. Wilkinson et al., 2024). This paper argues that the FAIR principles can advance effective and transparent scholarly communication about theory. To this end, we introduce "FAIR theory": a digital instantiation of a scientific theory, published as a self-contained and citable information artifact distinct from the scientific paper, compliant with the FAIR principles. FAIR theory has the potential to improve the efficiency of scholarly communication and accelerate cumulative knowledge acquisition. We focus on applications in psychology, but the principles are relevant across the social sciences, and beyond.

The Need for FAIR theory

The so-called "replication crisis" has prompted extensive reforms in psychology and other scientific fields (Lavelle, 2021; Scheel, 2022). Concern that undisclosed flexibility in analyses was a major factor for the abundance of non-replicable findings led to widespread adoption of open science practices like preregistration and replication (Nosek et al., 2015). These various practices ensure transparent and repeated testing of hypotheses. However, recent reviews show that most preregistered hypothesis tests are not supported by empirical evidence (Scheel, Schijen, & Lakens, 2021). Thus, increased rigor in testing has revealed that the root cause of the replication crisis is more fundamental: Psychological theories rarely provide hypotheses that are corroborated by evidence. Furthermore, theories are often so vague that they can accommodate mutually inconsistent findings, as the theory's central claims evade falsification. A good example of this is found in "self-determination theory"

(SDT), which emphasizes the role of intrinsic and extrinsic motivation in human behavior. Initially, intrinsic motivation was understood as engaging in an activity purely for the inherent satisfaction it provides, free from any external rewards or pressures (Deci, 1971). Over time, however, SDT expanded its definition to include motivations driven by the fulfillment of basic psychological needs—autonomy, competence, and relatedness—all still categorized as "intrinsic" (Ryan & Deci, 2000). The profound difference between these definitions becomes clear when considering the act of changing a child's dirty diaper. Under the original definition, few would be considered intrinsically motivated, after all, it's not exactly a joy-filled experience Yet, under the expanded framework, many would be, as the act may fulfill deeper needs, such as the desire to nurture and care for one's child.

Scholars have been raising concerns about the state of theory in psychology for nearly 50 years (Meehl, 1978; Robinaugh, Haslbeck, Ryan, Fried, & Waldorp, 2021). One main concern is that theories lack precision, or *formalization* (Szollosi & Donkin, 2021). When theories do not make precise predictions, they are hard to falsify and difficult to understand on their own, without either substantial interpretation or additional background knowledge. A second concern is the lack of transparent and participative scholarly communication about psychological theory, which limits its progression and development.

Given these concerns, it is an imbalance that scientific reform initiated by the open science movement has focused primarily on improving deductive methods. The equally critical inductive processeses of theory construction and improvement have been largely overlooked[1]. The present paper restores balance by applying, for the first time, open science principles to psychological theory. We apply the FAIR principles to scientific theories, introducing *FAIR theory* to facilitate transparent scholarly communication and accelerate cumulative knowledge acquisition.

[1] We use induction to describe inferences from specific observations to general theories. Others have used the term "abduction", coined by Peirce to describe "inference to the best explanation". However, Peirce later acknowledged that abduction "is not essentially different from induction" (Peirce, 1960, p. 4881). As defining what makes a theory "best" requires auxiliary assumptions, we consider abduction to be a special case of induction. For present purposes, however, the terms are interchangeable.

Theory and Scientific Progress

According to the *empirical cycle* (de Groot, 1961), a meta-theoretical model of cumulative knowledge acquisition, research ideally follows a cyclical process with two phases, see Figure 1, panel (a). In the deductive phase, hypotheses derived from theory are tested on data. In the inductive phase, patterns observed in data are generalized to theoretical principles. In this model, theories are the vehicle of scientists' understanding of phenomena. Ideally, they are iteratively updated based on deductive testing and inductive theory construction.

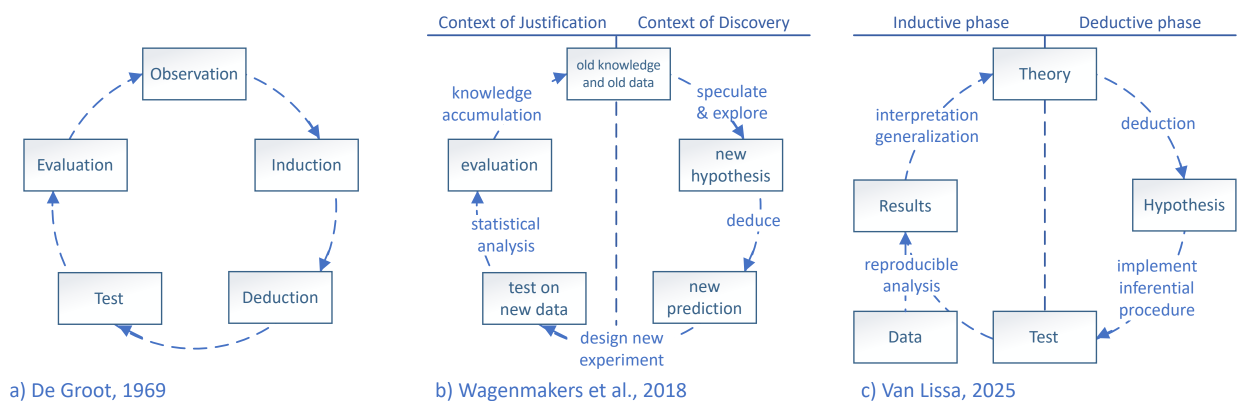

Figure 1. Three implementations of the "empirical cycle".

In a progressive research program (Lakatos, 1971), this cycle is regularly completed to iteratively advance our understanding of the studied phenomena. There are, however, indications that contemporary psychology falls short of this ideal. Firstly, because hypothesis-testing research is over-represented in the literature: According to Kühberger, Fritz, and Scherndl (2014), 89.6% of papers published in psychology report confirmatory hypothesis tests. Closer examination of deductive research reveals, however, that the link between theory and hypothesis is often tenuous or absent (Oberauer & Lewandowsky, 2019; Scheel, Tiokhin, Isager, & Lakens, 2021). Only 15% of deductive studies referenced any theory, and theory was often not cited in relation to the hypothesis (McPhetres et al., 2021). The remaining 85% of deductive studies lacked an explicit connection between theory and hypothesis. Perhaps some of these ungrounded hypotheses are rooted in implicit theories privy only to the author, in which case it would be straightforward and important to make these explicit Norouzi, Kleinberg, Vermunt, & Van Lissa (2024). Or, perhaps some hypotheses are thoughtlessly reported as part of entrenched research practices (Gigerenzer, Krauss, & Vitouch, 2004), but are not of substantive interest, such as null hypotheses that exist solely for the purpose of being rejected (Van Lissa et al., 2020). Testing ad-hoc hypotheses not grounded in theory does not advance our principled understanding of psychological phenomena. Put differently: collecting significance statements about ad-hoc hypotheses is much like trying to write novels by collecting sentences from randomly generated letter strings (van Rooij & Baggio, 2021).

Theory thus has an uncomfortable and paradoxical role in contemporary psychology: The majority of papers ostensibly test hypotheses, but these are rarely connected to, let alone derived from, theory. Moreover, test results do not routinely contribute to the improvement or rejection of theories. The paradoxical role of theory in psychology is perhaps best described by Meehl's observation that theories in psychology "lack the cumulative character of scientific knowledge. They tend neither to be refuted nor corroborated, but instead merely fade away as people lose interest" (Meehl, 1978).

Making Theory FAIR

The present paper introduces open science methods for theory specification and archival. Merely publishing theory in a research article does not make it open; to be open, theory should adhere to established open science standards. We do so by implementing theories as information artifacts, archived with apropriate metadata in a FAIR-compliant repository (e.g., Zenodo). Metadata are "data about the data", they provide information about the nature and content of an information artifact. Metadata are stored in the repository where the version of record of the FAIR theory is deposited. FAIR theories are *Findable* via a DOI or by searching the repository they are archived in; *Accessible* in a machine- and human-readable filetype; *Interoperable* for specific purposed, for example, within the data analysis environment; and *Reusable* in the practical and legal sense, so that they may be iteratively improved by the author or by others. Following the original proposal of Lamprecht and colleagues, we adapt the FAIR principles for theory, see Supplemental Table S1. We reflect on the necessary changes (which are minor), as well as on the current state and future of FAIR theory in psychology. The resulting principles provide guidance for instantiating theory as a FAIR information artifact, and we provide worked examples to encourage their adoption.

What is Theory?

Definitions of theory abound and are the subject of extensive scholarly debate. Given that a pluriformity of definitions are consistent with FAIR theory principles, the method is not contained to any one particular definition. Perspectives on scientific theory have been categorized as syntactic, semantic, and pragmatic (Winther, 2021) The syntactic view describes theories as "sets of sentences in a given logical domain language" (Winther, 2021, ch. 2), acknowledging that each domain (a scientific field, such as psychology or physics) has its own theoretical vocabulary. We recognize the syntactic view in Meehl's hierarchy of ever-more specific "statements" a theory might contain (1990): statements about the types of entities postulated (i.e., ontology), statements about causal connections between those entities, statements about the functional form of those connections, and statements about their specific numerical values (cf. Frankenhuis, Panchanathan, & Smaldino, 2023; Guest, 2024).

The semantic view challenges the necessity of distinct domain languages for different scientific fields, and instead advocates for formalizing theories using mathematics. It shifts the focus from theories as collections of sentences to mathematical models. The term "model" is not uniquely defined within the literature; it has been described as a "specific instantiation of theory narrower in scope and often more concrete, commonly applied to a particular aspect of a given theory" (Fried, 2020). This implies that theories and models are not fundamentally distinct, but rather, that for each model, there is a more general theory that subsumes it (one person's model is another person's theory). The pragmatic view holds that there might not be one structure or definition of scientific theories, but instead, definitions differ across scientific domains. It also argues that nonformal aspects (e.g. commonly used analogies) and practices (e.g. experimental designs) can be an important part of scientific theories.

It is best left to the scholarly community to decide which parts of theory, models, or other aspects should be represented as FAIR theory. As the practice of FAIRification becomes more embedded, we expect that it will become increasingly clear what kind and form of information is useful. As a particular FAIR theory evolves, details may be added, and the nature of the information tracked might even change. For example, following Meehl, we could envision a theory that starts out with establishing, through observation, an ontology of constructs relevant for a given phenomenon. After initial exploratory research, the theory might be further specified by making assumptions about how these constructs are causally connected. Over time, more precise *statistical/mathematical models* could be derived by further assuming a specific functional form for relationships (e.g., linear effects) and error families for the distribution of measured variables (e.g., normal distributions). This allows for the specification of statistical models, which make just enough assumptions to allow the estimation of the remaining unknown parameters (e.g., regression slopes) from data. Going even further, a *generative/computational model* could be specified, which is completely parameterized (i.e., specific values of regression slopes are also assumed) such that an interpreter (e.g., the R programming language) can use the model to generate new data. Also, aspects of scientific practice might be added over time - either to the theory itself, or as references recorded in the theory metadata. Examples include experimental designs (e.g. longitudinal designs observing change over time), measurement tools (e.g. different questionnaires used to assess the same construct), or study subjects (e.g. specific strains of rats).

As an applied example, consider a comprehensive theory of disease spread and pandemics which covers various psychological factors such as adherence to infection prevention protocols (e.g., social distancing), pandemic-related behavior (e.g., panic buying), and pandemic-related distress (Taylor, 2022). The theory may encompass a particular transmission *model* for disease spread including precise parameters for the process of infection (e.g., social distance, average duration of encounters, ventilation) and incubation times.

The Role of Theory Formalization. Concerns about the state of theory in the psychological literature revolve around two issues: theory formalization and theory (re-)use. Greater formalization increases theories' *empirical content* (Popper, 2002) because it expresses ideas as precise statements, clearly demarcating what should (not) be observed. For example, Baddeley's verbal description of the phonological loop in his theory of working memory allows for at least 144 different implementations depending on the specification of the decay rate, recall success, or rehearsal sequence (Lewandowsky & Farrell, 2010). Without committing to specific implementations a-priori, the theory becomes hard to test. Compared to theories expressed in natural language, formal theories facilitate inconsistency checking and evaluation of a theory's (lack of) ambiguity. Committing to specific implementations of the different components, their causal connections, and the functional forms of these relationships makes the theory more precise. More precise theories are easier to falsify, which necessitates specific revisions and advances our principled understanding of the phenomena they describe.

FAIR theory imposes no restrictions on the manner in which theories are derived and implemented; rather, it increases the fidelity and ease with which they are communicated. Thus, FAIR theory does not require theories to be formal, and formal theory can be represented in a way that is not FAIR. The FAIR principles pertain to theories' metadata documentation and sharing in digital archives, with the aim of enhancing their reusability and extensibility. They can be applied to theories representated in natural language, as well as formal theories represented using mathematical notation, algorithmic pseudo code, or a set of logical clauses. Thus, for example, “grounded theory”, derived from qualitative research, can be represented as a FAIR theory if it is represented as plain-text propositions and archived in a FAIR repository with appropriate metadata. Conversely, a formal theory is not FAIR if it is confined to in a journal article without any key words to identify it as a theory paper (lacking Findability), represented as a bitmap image (limiting Accessibility and Interoperability), and behind a paywall (limiting Reusability). FAIR theory is thus consistent with, but does not require, formalization (also see *Accessibility*).

Modular Publishing. We propose FAIR theory as an instantiation of modular publishing (Kircz, 1998). In most fields, the primary unit of scientific communication is the academic paper. A paper may depend on multiple resources - materials, data, code, and theory - but these are often merely described in the text. Modular publishing is the practice of making each of these resources available as independent citable *information artifacts* in their own right, with adequate metadata that is indexed in standardized repositories (Van De Sompel, Payette, Erickson, Lagoze, & Warner, 2004). Data sharing is a good example of a modular publishing practice that is widely adopted and increasingly required by funding agencies, journals, and universities. Scholars can archive information artifacts in repositories like Zenodo, which was developed by CERN under the European Union’s OpenAIRE program. To maintain a persistent record of scholarly communication, Zenodo mints DOIs for information artifacts - as does, for example, the Crossref association, which is used by many academic publishers. Finally, the DataCite Metadata Schema offers a standard way to document the nature of relationships between information artifacts (DataCite Metadata Working Group, 2024). For example, a dataset collected for a specific paper would be archived in Zenodo with the metadata property `resourceType: dataset`, and cross-reference the published paper with `relationType: IsSupplementTo`. Similarly, a FAIR theory object can be connected to a specific paper which might serve as the theory’s documentation and canonical reference by using `relationType: IsDescribedBy`, while the reverse relationship, documented in the canonical reference paper, is `relationType: Describes`. Other types are useful for making relationships between multiple theory objects explicit: If an existing theory is made FAIR without substantial alterations, the resulting FAIR theory metadata would cross-reference the existing theory as `relationType: IsDerivedFrom`. If an existing theory is updated, `relationType:IsNewVersionOf` could be used to reference previous versions. If a variation of an existing FAIR theory is created, cross-reference it with `relationType: IsVariantFormOf`.

Version Control. We can take inspiration from the field of computer science for well-established processes for iteratively improving information artifacts. Version control systems, like Git, have long been used to iteratively improve computer code, while managing parallel contributions from collaborators and allowing for experimentation and diverging development without losing information. Git tracks line-by-line changes to text-based files, and maintains a complete history of those changes. It has long been argued that Git is particularly well-suited to academic work (Ram, 2013). Git can be used, for example, to facilitate reproducible research, manage distributed collaboration, and improve preregistration (Peikert, Van Lissa, & Brandmaier, 2021; Van Lissa et al., 2021). The present paper considers the advantages of Git for FAIR theory. Git enables explicitly comparing versions of a file (or: theory), incorporating changes by different authors, and branching off into different directions (e.g., competing hypotheses) while retaining an explicit link to the common ancestor. This makes it possible for meta-scientists to study the provenance of a theory and determine how well different versions of a theory explain empirical evidence (Van Lissa, 2023).

Semantic Versioning. Aside from technical solutions, version control is a social process as well. On the one hand, regular updates can improve theories - but on the other hand, it risks breaking compatibility between theories and hypotheses derived from them, or compatibility between one theory and others that depend upon it. For example, if we construct a theory to explain a specific phenomenon, and we cross-reference an existing theory comprising an ontology for our field - that dependency is broken if the ontology is later updated and our phenomenon of interest is removed. In computer science, these challenges are navigated by assigning version numbers. Specifically, *semantic versioning* comprises a simple set of rules for assigning version numbers to information artifacts. Whereas version control tracks changes, semantic versioning communicates what those changes mean to users of the theory, guides the social process of theory development, and signals how much a theory has been changed. We propose the following adaptation of semantic versioning for theories:

```
Given a version number MAJOR.MINOR.PATCH, increment the:

MAJOR version when you make backwards incompatible changes, i.e., the
      theory now contains empirical statements that are at odds with
      a previous version
MINOR version when you expand the set of empirical statements in a
      backward compatible manner (i.e., the previous version is
      subsumed within the new version)
PATCH version when you make backward compatible bug fixes, cosmetic
      changes, fix spelling errors, or add clarifications
```

The FAIR Principles

Findability

Making theories Findable would allow researchers to easily identify relevant theories and ground their hypotheses in established theoretical foundations. It further increases the impact and reuse potential of theories across disciplines, either through direct application (where one discipline stumbles upon a problem that is already well-understood in another discipline), or through analogical modeling. In analogical modeling, the structure of a theory from one discipline is applied to a phenomenon in another field. For example, predator-prey models have inspired theories of intelligence (Van Der Maas et al., 2006), and the Eysenck model of atomic magnetism has inspired a network theory of depression (Cramer et al., 2016). Findability also enables meta-research on theories, in the same way libraries and search engines have enabled scholars to study the literature via systematic reviews. In a similar way, it would become much easier to explicitly compare different theories of a specific phenomenon, or to study structural properties of theories.

The four Findability criteria are applicable to theory with only minor adjustments, see Supplemental Table S1. First, this requires assigning a globally unique and persistent identifier, such as a DOI, to each theory (F1). Of the many services that provide DOIs for scientific information artifacts, Zenodo and the Open Science Framework are commonly used in psychology. Second, Findable theory is described with rich metadata (F2). This includes citation metadata (e.g., referencing a scientific paper that documents the theory, or a psychometric paper that operationalizes specific constructs). It might further include domain-specific metadata, such as a reference to a taxonomy of psychological constructs (Bosco, Uggerslev, & Steel, 2017), ontology (Guyon, Kop, Juhel, & Falissard, 2018), or catalog of psychological phenomena. Metadata should also include identifiers for all the versions of the theory it describes (F3); Zenodo handles this by default by providing an overarching DOI for an information artifact which subsumes the DOIs of that artifact's versions.

Finally, metadata should be registered or indexed in a searchable registry (F4). It is important to note that, while may archives are technically searchable (e.g., GitHub, FigShare, the Open Science Framework, institutional repositories), only few are specifically designed for FAIR-compliant archival. Zenodo stands out in this respect. Thus, while using Git for version control and GitHub for collaboration has specific advantages for scientific work (Ram, 2013), the version of record should be archived in a FAIR repository like Zenodo. Using standardized metadata further improves the Findability of theories archived within

FAIR repositories. The DataCite Metadata Schema provides a controlled vocabulary for research output, and the `resource_type: model` matches the description of FAIR theory (DataCite Metadata Working Group, 2024). Furthermore, we suggest using the keyword `"fairtheory"` for all resources that constitute or reference (a specific) FAIR theory.

Findability is substantially amplified if intended users of a resource know where to search for it. This is a known problem in relation to research data and software (Katz & Chue Hong, 2024). Regrettably, most academic search engines only index traditional print publications, not other information artifacts. Since the status quo is to publish theories in papers, the FAIR requirements are met if scholars continue to do so, and additionally publish theories as separate information artifacts. The `"fairtheory"` keyword can also be used to signal the presence of theory within a paper. In the longer term, it may not be necessary to write a paper for each theory. If Zenodo becomes more recognized as centralized repository for information artifacts, researchers may begin to search there more regularly. Conversely, as organizations begin to recognize the value in tracking academic output other than papers, repositories may begin to index information artifacts stored in Zenodo.

There have been notable efforts to improve theories' Findability through post-hoc curation. For example, Gray and colleagues introduced a format for representing theories, and post many examples on their website (Gray, 2017). Similarly, Van Dongen and colleagues are working on a database of models and formalized theories. Post-hoc curation is a notable effort but does not address the root cause of the lack of Findability. Ideally, Findability would be addressed ante-hoc, through documentation with rich metadata and modular publishing. Both approaches can be complementary, however. for example, post-hoc curation could make use of existing FAIR-compliant archival infrastructure like Zenodo. Conversely, the database engineering adage "Lots of Copies Keeps Stuff Safe" (LOCKSS) implies that it is fine to archive theories in multiple places, although it is advisable to make use of automatic integration (as exists between GitHub, Zenodo, and OSF) to avoid the need to maintain information in multiple places, which increases the risk of inconsistencies arising.

Accessibility

Transparent scholarly communication about theory requires that theories are Accessible to all researchers and other stakeholders. If theories are not Accessible, researchers cannot reuse and refine them. Thus, Accessibility can accelerate cumulative knowledge acquisition. Making theories Accessible also allows stakeholders (e.g., practitioners, policymakers, advocates) to inform themselves of the current scientific understanding of specific phenomena. While isolated empirical findings can appear fragmented and contradictory (Dumas-Mallet, Smith, Boraud, & Gonon, 2017), theories offer a top-down, big-picture representation of the phenomena studied in a field. In other words, theories are an important instrument in science communication.

The Accessibility principles are sometimes misunderstood as pertaining to *maximizing* access; rather, they should be understood as *regulating* it. They apply to theory with minor changes. Firstly, theory and its associated metadata should be Accessible by their identifier using a standardized communications protocol (A1). This can be achieved, for example, by hosting theory in a version-controlled remote repository (such as Git), and archiving that repository on Zenodo for long-term storage. The resulting resource will then have an identifier (DOI) which allows the theory to be accessed using a standardized communications protocol (download via `https` or `git`). Secondly (A2), theory metadata should be Accessible, even when the theory is no longer available, which is also achieved via long-term storage (e.g., on Zenodo). Git remote repositories allow for access control, and Zenodo allows for access control of individual files/resources. In general, it makes sense to retain outdated theories, in order to be able to track the genesis of theories over time, yet, we require the availability of meta data as a minimum requirement.

At present, there are several impediments to theories' Accessibility. To the extent that theories are still contained within papers, paywalls erected by publishers constitute a barrier. Open Access publishing increases the Accessibility of all academic output, including theory.

A second impediment is more indirect: While open access publishing increases practical access to theories, Accessibility also requires clear and explicit communication. This property of good theories has been dubbed "discursive survival [. . .], the ability to be understood" (Guest, 2024). At present, psychological theories are often ambiguous, rendering them difficult to understand (Frankenhuis et al., 2023). It is important to acknowledge the *indeterminacy of translation* (Quine, 1970): which holds that every communicative utterance (e.g., a statement in natural language, a mathematical formula, et cetera) has multiple alternative translations, with no *objective* means of choosing the correct one. It follows that an idea cannot be formalized to the point that it becomes unambiguously interpretable. This places a theoretical upper bound on theories' ability to be understood.

Successful communication requires shared background knowledge between sender and receiver (Vogt et al., 2024). The notion of "normal science" describes a phase in which a scientific community operates within the context of a shared paradigm, creating the background knowledge needed for mutual understanding and productive scientific work (Kuhn, 2009). In real life, paradigms are rarely clear-cut, and shared background knowledge can come from different sources, including education, cultures of communication, and availability of particular instruments for observation, measurement, and analysis - or it can be problematically absent.

A third impediment arises when theories have, what we call, a "dependency on the author" (DOA). DOA occurs when a theory cannot be understood by independent scholars, requiring the original author to provide interpretation and clarification. DOA relates to the discourse on "Great Man Theorizing" (Guest, 2024) because it enables gatekeeping: an author could insist that work requires their involvement or denounce work conducted outside their purview as illegitimate, which violates checks and balances of scientific research. DOA also renders theories immune to refutation, because the author can claim that the theory was misconstrued when confronted with falsifying evidence, thus making it a moving target (Szollosi & Donkin, 2021). DOA is inherently problematic, as illustrated by cases where third parties identify logical inconsistencies within a theory (e.g., Kissner, 2008). This example demonstrates that original authors are not the ultimate authority on their theories. DOA thus unduly impedes scientific progress, and authors should make good-faith efforts to make theories as Accessible as possible, in terms of both availability and interpretability.

In sum, while it is impossible to communicate a theory completely unambiguously, scholars should strive to reduce unnecessary ambiguity to the greatest possible extent. It may benefit scientific discourse to normalize explicit ambiguity (these are things we don't know yet) and anticipate misunderstanding, to invite others to fill in the blanks and motivate ever further explication of theory. A theory's Accessibility is increased by reducing dependencies on (implicit) background knowledge, explication of assumptions, formalization, and explicit cross-references to relevant resources such as papers, ontologies, macro-theories, measurement instruments, experimental designs [REF LANGE CHECKLIST].

Interoperability

Interoperability pertains to the property of information artifacts to "integrate or work together [...] with minimal effort" (M. D. Wilkinson et al., 2016b). Firstly, theory and its associated metadata should use a formal, accessible, shared and broadly applicable language to facilitate (human- and) machine readability and reuse (I1). The common practice of instantiating theory as lengthy prose or schematic drawing falls short of this ideal. Instead, FAIR theory should, ad minimum, be instantiated in a human- and machine-readable datatype, as should all information artifacts created while performing scholarly work (Van Lissa et al., 2021). Depending on the level of formalization of the theory, different formats may be appropriate, such as verbal statements in plain text, mathematical formulae, and statements expressed in some formal language. Examples of the latter include pseudo-code, interpretable computer code, and Gray's theory maps (Gray, 2017). While a theory represented as a bitmap image is not very Interoperable, the same image represented in the DOT language ("DOT Language," 2024) for representing graphs does meet this ideal.

Secondly, theory (meta)data should use vocabularies that follow FAIR principles (I2). Aside from the aforementioned Datacite metadata schema (DataCite Metadata Working Group, 2024), in the context of theory, this highlights the importance of establishing standardized ontologies. Thirdly, theory (meta)data should include qualified references to other (meta)data, including previous versions of the theory (I3). The first part of this principle allows for nested theories; for example, a theory that specifies causal relationships between constructs could refer back to an ontological theory from which those constructs are derived. This can be achieved by cross-referencing the DOI of those nested theories ("Contributing Citations and References," 2024). The second part of this principle allows for tracing the provenance of a theory; keeping track of its prior versions and other theories that inspired it. This is achieved by using Git for version control and Zenodo for archiving. Git tracks the internal provenance of a theory repository; Zenodo is used to cross-reference external relationships (e.g., papers that influenced the theory, previous theories that inspired it, models based upon the theory).

Recent work points out that Interoperability is not an all-or-nothing property. The concept of X-Interoperability was introduced to answer the question: *Interoperable for what?* X-Interoperability is defined as facilitating "successful communication between machines and between humans and machines [, where] A and B are considered X-Interoperable if a common operation X exists that can be applied to both" (Vogt et al., 2024). This revised definition makes it possible to outline a theory's affordances in terms of X-Interoperability. For example, a FAIR theory may be X-Interoperable for deriving testable hypotheses, or for the purpose of selecting relevant control variables, or for the purpose of indicating the conditions necessary for observing a particular phenomenon. If we consider Meehl's nine properties of strong theories (properties 3-8 are grouped because they all refer to functional form), we see how each of these properties incurs certain affordances in terms of X-Interoperability (Table 1).

With regard to the state of Interoperability in psychology, Kurt Lewin's -Lewin (1943)

Table 1

Property	X-Interoperability
1) Ontology	Variable selection
2) Causal connections	Model specification, covariate selection, causal inference
3-8) Functional Form	Deriving specific hypotheses
9) Numerical Value	Simulating data

adage “there’s nothing as practical as a good theory” paints a hopeful picture of theories as useful tools in psychological researchers’ day-to-day work. But, as we argued, this is not the case. The examples of X-Interoperability offered in Table 1 illustrate that much can be gained by integrating theory directly into analysis workflows, and by making theory X-Interoperable within software used for analysis. For example, Interoperable theory could be used to select control variables for causal inference (Cinelli, Forney, & Pearl, 2022), or to preregister the inferential procedure that would lead to specific modifications of a theory after analyzing empirical data (Peikert et al., 2021), or to derive machine-readable hypotheses (Lakens & DeBruine, 2021) which could be automatically evaluated through integration testing (Van Lissa, 2023). Furthermore, theories can be X-Interoperable with each other to enable nesting, or using one theory to clarify elements of another theory. For example, it should be possible to embed a theory about emotion regulation (e.g., Gross, 2015) within a theory of emotion regulation development (Morris, Silk, Steinberg, Myers, & Robinson, 2007).

Reusability

If we take cumulative knowledge acquisition to be a goal of scientific research, then Reusability is the ultimate purpose of making theory FAIR. Applied to FAIR theory, reusability requires that each theory and its associated metadata are richly described with a plurality of accurate and relevant attributes (R1) with a clear and Accessible license for reuse (R1.1). It should further have detailed provenance (R1.2), which is achieved through version control with Git and archival on Zenodo. Finally, the (meta)data which meets domain-relevant community standards (R1.3). The Datacite metadata schema offers an initial template in this regard, and this paper takes one step towards establishing more fine-grained community standards for FAIR theory. This is an example of FAIR metadata extracted from Zenodo.

If we consider the current state of Reusability in psychological theory, there appears to be a norm against theory reuse: *"[Theories are] like toothbrushes — no self-respecting person wants to use anyone else's"* (Mischel, 2008). As cumulative knowledge acquisition requires reusable theories that are continuously updated based on insights from new data, such a norm impedes scientific progress (de Groot, 1961). In FAIR theory workshops, we similarly notice a reluctance to reuse and adapt existing theories. Students ask questions such as "Who owns a theory?", and "Who determines how a theory may be reused or changed?". These questions imply a norm against modifying theory without its author's consent, reminiscent of the aforementioned problem of dependency on the author.

Licensing theories for reuse unambiguously answers these questions, with the caveats that legislation may vary across contexts and jurisdictions, and that this paper does not constitute legal advice. Two considerations are important when determining what license is appropriate for theory. A first consideration is that copyright law protects authors' rights according to the idea-expression dichotomy (Bently, Davis, & Ginsburg, 2010). It explicitly does not *"extend to any idea, procedure, process, system, method of operation, concept, principle, or discovery"*. Copyright thus applies to creative works expressing a theory (e.g., prose, visual illustrations), but not to the underlying theoretical idea. It thus seems that theories expressed in prose or depicted visually - in other words, that fall short of the Accessibility criterion - are more likely to qualify for copyright protection than formal theories. A second consideration is that academic research is covered under "fair use" exemptions to copyright. Given these two considerations - that copyright does not protect ideas in their purest form and that academic use offers exemptions to copyright - it may be counterproductive and possibly misleading to adopt a license that assumes copyright protection to theories. For psychological theories without commercial aspects, we suggest using a licence that explicitly waives copyright and encourages Reusability, such as CC0 (no rights reserved).

Aside from legal conditions for reuse, there are also social considerations. For example, while a CC0 license does not legally mandate attribution, the norms of good scientific practice mandate that scholars comprehensively cite theory and related works (Aalbersberg et al., 2018). Particularly when FAIRifying an existing theory, failing to credit its author amounts to scientific malpractice. Another instrument for guiding the social process of (diffuse) collaboration is to include a "README" file in the theory repository, which informs users about the ways in which they can reuse and contribute to a FAIR theory. A final suggestion is to create or adopt a "Code of Conduct" which prescribes behavioral norms for contributors and users of a theory (Ehmke, 2014).

Making a Theory FAIR

To concretize the FAIR principles, we propose an applied workflow for making theory FAIR. The guiding principle of our approach is to align and build upon existing successful open science infrastructures to the greatest possible extent. At the time of writing (2024), the value of using Git for version control of academic research is well-established (Ram, 2013), and the integration of GitHub and Zenodo makes for a particularly user-friendly approach that meets *all* of the FAIR principles (Supplemental Table S1). Zenodo and GitHub are both integrated with the Open Science Framework (OSF), a popular platform in psychology. Thus, it is possible to create a project page on the OSF to increase the visibility of a FAIR theory amongst users of that platform, while the integration of the OSF with Zenodo and GitHub removes the need for maintaining the same information on multiple platforms. Note that open science infrastructure is an area of active development, and as such, the approach proposed here might change. Our workflow can be largely automated in R using the `theorytools` package. To anticipate workflow changes, the package includes a living document with the most recent version of our proposed workflow. It can be accessed by running `vignette("fairtheory", package = "theorytools")` in R. We present a brief summary of the instructions at the time of writing here, to illustrate the general principles of FAIRifying theory which can also be implemented using other open science infrastructures.

1. Implementing the Theory

We will use the *empirical cycle* as a running example for this tutorial. The empirical cycle, described on page 28 of De Groot and Spiekerman (1969), is a meta-theory of theory construction. The resulting FAIR implementation of this theory is available at https://doi.org/10.5281/zenodo.14552329. The original theory consists of a series of natural language statements:

> *Phase 1:* 'Observation': collection and grouping of empirical materials; (tentative) formation of hypotheses.
> *Phase 2:* 'Induction': formulation of hypotheses.
> *Phase 3:* 'Deduction': derivation of specific consequences from the hypotheses, in the form of testable predictions.
> *Phase 4:* 'Testing': of the hypotheses against new empirical materials, by way of checking whether or not the predictions are fulfilled.
> *Phase 5:* 'Evaluation': of the outcome of the testing procedure with respect to the hypotheses or theories stated, as well as with a view to subsequent, continued or related, investigations.

If we compare it to the levels of theory formalization (Guest & Martin, 2021), it is defined at either the "theory" or "specification" level. We can increase the level of formalization, and present an "implementation" in the human- and machine-readable DOT language (and thereby fulfill criterion I1 of Supplemental Table S1). The implementation below describes the model as a directed graph. Note that the code has been organized so that the first half describes an ontology of the entities the theory postulates, and the second half describes their proposed interrelations. This follows the first two properties of good theory according to Meehl (Meehl, 1990). We can save this implementation of the empirical cycle to a text file, say `empirical_cycle.dot`.

```
digraph {

  observation;
  induction;
  deduction;
  test;
  evaluation;

  observation -> induction;
  induction -> deduction;
  deduction -> test;
  test -> evaluation;
  evaluation -> observation;

}
```

2. Creating a Project Folder

Create a new folder and copy the theory file from the previous step into it. To help meet the Interoperability and Reusability criteria, add two more files: A README.md file with instructions for future users of your theory, and a LICENSE file with the legal conditions for reuse. For guidance on writing the README file, see this vignette We recommend the `CC0` license, but other options are available, see https://choosealicense.com.

3. Version Control the Repository

The field of computer science provides well-established processes for creating information artifacts that can be iteratively improved. In particular, the practice of version control offers extensive benefits for scientific work (Ram, 2013; Van Lissa et al., 2021). To version control our project, we initiate a Git repository in the project folder. We subsequently create a remote repository to host a copy of this local Git repository on GitHub, which will in turn be archived. Note that the repository must be set to "Public" to take advantage of GitHub's Zenodo integration. Push the local files to the Git remote repository, and keep them synchronized going forward.

4. Archive the Theory on Zenodo

First, create a Zenodo account with your existing GitHub account. Then in Zenodo, go to the GitHub section under your account. Following the instructions on the page, activate Zenodo for your theory repository. Then, create a new release of the GitHub repository. Choose a tag and release title using our adapted semantic versioning, starting with version 1.0.0, if you intend to share your theory with the broader scientific community. After publishing the release, you should be able to see the archived version in your Zenodo account, along with a DOI.

5. Entering Meta-Data

By default, Zenodo assumes that GitHub repositories contain software and documents them as such. To document our archive as a FAIR theory requires adding some extra information on Zenodo. Supplying the information below helps improve the Findability of a theory. See here for an example of the resulting FAIR metadata archived in Zenodo.

- Set the *resource type* to `Model`; this ensures proper archival in Zenodo
- Verify that the *title* is prefaced with `FAIR theory:`; this allows sentient readers to recognize the work as a FAIR theory

- Add the *keyword* `fairtheory`; this aids search engine indexation
- Optionally, submit the theory to the "FAIR Theory Community" to contribute to community building
- List the DOIs/identifiers of *related works*. Use the `Relation` field as appropriate. For example:
  - `Is documented by` can be used to reference a theory paper you wrote, in which you introduce this FAIR theory
  - `Is derived from` could be used to reference a paper or book chapter that introduced an existing theory that was not previously made FAIR. We used `Is derived from` to reference De Groot and Spiekerman's empirical cycle.

Automating these Steps

R-users can use the `theorytools` package to partly automate the preceding steps, for example, using following code (see the package documentation for more information):

```
install.packages("theorytools")
library(theorytools)
# Use worcs to check if GitHub permissions are set:
library(worcs)
check_git()
check_github()
# Create the theory repository:
fair_theory(path = "c:/theoryfolder/empirical_cycle",
            title = "The Empirical Cycle",
            theory_file = "empirical_cycle.dot",
            remote_repo = "empirical_cycle",
            add_license = "cc0")
```

Updating a Theory

De Groot's empirical cycle has inspired several authors, but not all of them have interpreted his work the same. For example, Wagenmakers and colleagues' (2018) interpretation of the empirical cycle diverges substantially from De Groot's description. An important advantage of FAIR theory is that we can implement different versions of a theory, compare them, and document their cross-relationships. We can take work that has been done before - in this case, the repository created above, and create an independent copy that we can modify as we wish, while retaining cross-references to the original. Wagenmakers and colleagues' version can also be implemented as a DOT graph to illustrate some clear deviations from the original. Notice that, first, the phases of the cycle have been renamed. This change was not described in the paper. If we assume that the labels are meant to illustrate the phases, not substantially change the ontology, then we can represent it by adding labels to the original DOT graph. The labels do suggest a focus on empirical psychology not present in De Groot's version. Furthermore, the label "knowledge accumulation" invites the question of exactly *how* knowledge accumulates upon evaluation of a prior experiment. As this lack of cumulative knowledge acquisition appears to be precisely where contemporary research practice falls short, this ambiguity invites further improvement of the theory. The authors explicitly mention a second change: *"We added the Whewell-Peirce-Reichenbach distinction between the context of discovery and the context of justification"*. The DOT graph below shows our implementation of this version of the empirical cycle, by adding subgraphs.

```
digraph {

  subgraph cluster_discovery {
    label="Discovery";
    induction [label="New hypothesis"];
```

```
    deduction [label="New prediction"];
  }
  observation  [label="Old knowledge and old data"];
  subgraph cluster_justification {
    label="Justification";
    test [label="Test on new data"];
    evaluation;
  }

  observation -> induction [label="Speculate & explore"];
  induction -> deduction  [label="Deduce"];
  deduction -> test  [label="Design new experiment"];
  test -> evaluation  [label="Statistical analysis"];
  evaluation -> observation  [label="Knowledge accumulation"];

}
```

The first author was inspired by De Groot as well, but again specified the empirical cycle differently. First, notice that the nodes in De Groot's formulation mostly refer to processes. This invites the question of what the deliverables are in each phase, or in other words: what actually changes when going through the cycle, except the scholar's mind. In the implementation below, we account for this difference by having the nodes refer to specific deliverables; the edges now refer to processes. Second, De Groot's distinction between phases of observation, induction, and deduction is not fully congruent with philosophy of science. Many have argued that observation is theory-laden, and as such, involves induction (Brewer & Lambert, 2001). Deriving hypotheses from theory is also not purely deductive, as auxiliary assumptions are often made (which, again, involves induction). Furthermore, if the testing procedure is not explicitly defined before seeing the data, it incurs some inductive bias as well (Peikert, 2023). With these alterations, we implement the empirical cycle as follows:

```
digraph {

  theory;
  prediction;
  data;
  test;
  results;

  theory -> prediction [label="deduction"];
  prediction -> test [label = "implement inferential procedure"];
  data -> results;
  test -> results [label = "apply to data"];
  results -> theory [label="interpretation and generalization"];

}
```

The FAIR theory workflow documented above offers several concrete ways to make changes to a FAIR theory object. If you start with an existing GitHub repository, and wish to make some changes to it, this is commonly done by creating a “branch”. A branch allows you to make non-destructive changes and can continue to exist in parallel to the main repository. Thus, it is possible to have one main theory with several branches that each contain competing theories derived from it. Figure 2 shows how our example `empirical_cycle` repository contains branches with Wagenmakers’ and Van Lissa’s implementations. A branch can also be merged with the main branch, thus incorporating the changes it contains into the version of record. If you wish to develop a new version of someone else’s FAIR theory, it is possible to “fork their repository”. This creates a copy of their repository onto your GitHub account. Both branches and forks can be compared and merged via "pull requests", which are essentially a request to incorporate the changes you have made. Figure 3 shows a comparison of the original empirical cycle by De Groot, and the lead author's implementation.

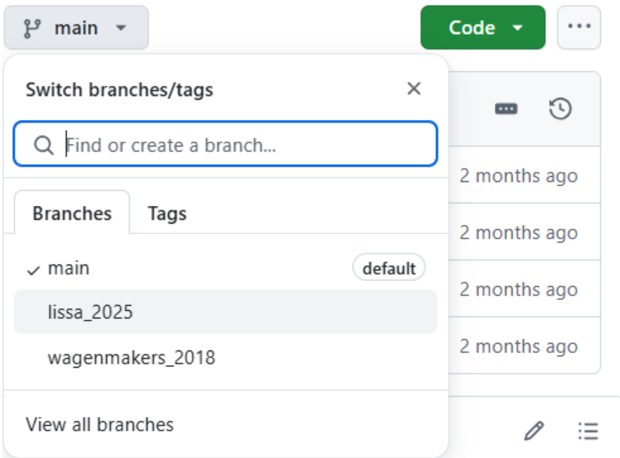

Figure 2. Branches can contain different versions of a theory.

Further Uses of FAIR Theory

As uses of FAIR theory are best illustrated using tutorial examples, the `theorytools` package contains several vignettes that showcase specific applications. At the time of writing, the package includes a vignette on theory specification, that is to say, moving from a theory represented as prose to a FAIR theory, based on the many-theorists project by Glöckner and Fiedler (in preparation). Another vignette illustrates the use of FAIR theory for causal inference (Pearl, 1995). Furthermore, one vignette illustrates the use of FAIR theory for conducting a simulation study. More vignettes may be added over time, and users are encouraged to submit their own reproducible examples as package vignettes.

Discussion

The replication crisis has brought the inadequacies of contemporary theoretical practices in psychology and other fields into focus. Psychological theories often fall short of all FAIR principles: they are hard to find and access, have limited Interoperability, and are

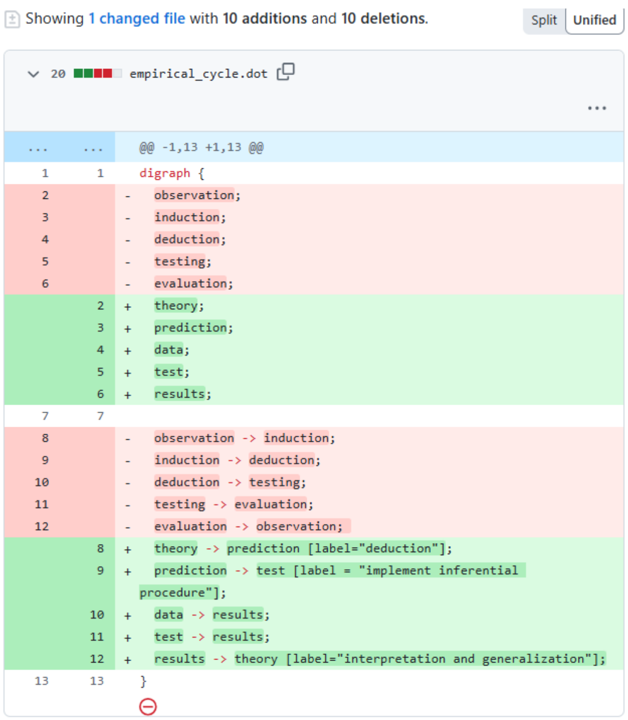

Figure 3. GitHub's compare functionality.

rarely Reused. These limitations impede cumulative knowledge production in our field, leading to an accumulation of "one-shot" empirical findings, without commensurate advancement in our principled understanding of psychological phenomena. We argued that applying the FAIR principles to theory offers a structured solution to these shortcomings. We demonstrated how to create, version-control, and archive theories as digital information artifacts. We introduced the `theorytools` R-package to partly automate these processes, reducing the barrier of entry for researchers, and creating a FAIR resource for theory construction tools and documentation that can be continuously updated as best practices develop further.

Making theory FAIR allows researchers to more easily find a relevant framework; access and understand it; interact with it in a very practical manner, for example, by deriving predictions from it, or using it to select control variables; and reuse it, contributing changes to existing theories or splitting of in a new direction. Whereas the idea of theory can be quite nebulous to empirical psychologists, FAIR theory makes theoretical work practical and tangible, incorporating theory into scholars' workflows. Having a concrete object to iterate upon facilitates the systematic improvement and iterative refinement of psychological theories, thus substantially increasing the efficiency of research. While FAIR theory does not directly reduce ambiguity, it provides a framework within which scholars can iteratively increase precision and formalization. The FAIR principles also facilitate new ways of collaboration, leveraging tools like Git for version control and Zenodo for archiving to document provenance and facilitate contributions from diverse researchers.

How to Incentivize FAIR Theory Development

FAIR theory requires a departure from contemporary practice. Several factors can expedite such a culture change. One key factor is the *recognition and rewards* movement: practices for evaluating scientific output are evolving, with initiatives like the *Declaration on Research Assessment* (DORA) and Coalition for Advancing Research Assessment promoting the use of more diverse and meaningful metrics beyond journal impact factors. Modular publishing capitalizes on these changing metrics, and publishing theories as citeable artifacts allows scholars to be credited for contributions to theory (Kircz, 1998). Journals that publish theoretical papers could require authors to additionally publish their theories in a FAIR format, cross-referencing the paper, to expedite its effective reuse and iterative improvement. A second factor is to lower barriers to adopting FAIR theory by building upon existing widely adopted open science infrastructures. For this reason, we advocate the use of Git for version control, Zenodo for archiving, and DataCite for standardized metadata. Barriers to entry can also be lowered by simplifying workflows, which is the goal of the `theorytools` R-package. Fourth, the availability of Open Educational Materials (OEM) about theory development contributes to doctoral socialization. These materials allow teachers to incorporate theory development into their curriculum without investing substantial time on course development, thus educating the next generation to make use of and contribute to FAIR theory. Finally, community building plays an important role; the international network of open science communities, reproducibility networks, and other similar initiatives provide platforms for disseminating FAIR theories and related methodological innovations. Authors can also share their FAIR theories with other early adopters by submitting them to the "FAIR Theory Community" on Zenodo.

Strengths

One important strength of FAIR theory is that it provides much-needed open science methods for the underemphasized inductive phase of the empirical cycle. Most extant open science methods focus on increased rigor in testing, but provide little guidance as to what to do with the newly collected empirical evidence. By providing much-needed open science methods for theory construction, FAIR theory helps restore the balance between inductive and deductive research and contributes to closing the "open empirical cycle" [REF Hoijtink].

Our approach aligns closely with contemporary developments in open science, such as modular publishing, interdisciplinarity, meta-research, and team science. The advantage of modular publishing is that authors can be credited for theory development. Given the current emphasis on empirical papers [REF], theoretical papers can be hard to publish. FAIR theories, by contrast, can be readily disseminated as citable information artifacts, thus changing the incentive structure to favor theory development.

Interdisciplinarity benefits from FAIR theory's Accessibility across different fields; thus, theoretical frameworks can be reused, adapted, or used for analogical modeling [REF Oisin paper]. Meta-research benefits from the fact that FAIR theory enables studying the structure, content, and development of theories over time. In terms of team science, FAIR theory facilitates collaboration by ensuring that all contributors have access to the same information and clarifying any remaining areas of contention or misunderstanding. Version control provides a framework to resolve parallel developments from multiple collaborators in a non-destructive manner. This facilitates collaboration across geographical boundaries, and adversarial collaboration, where others strive to falsify a theory or identify its inconsistencies, and democratizes collaboration with as-of-yet unknown collaborators via platforms like GitHub, where researchers outside one's network can identify issues or suggest improvements to theories.

Finally, FAIR theory plays an important role in science communication, because theory synthesizes contemporary scientific understanding about a phenomenon. Theory bridges the gap between academic research and practitioners by summarizing actionable insights, relieving practitioners from the need to sift through extensive empirical literature. By providing a mechanism for iterative improvement based on emerging evidence, FAIR theory also supports effective evidence-based decision making.

Limitations

One important limitation of the present work is that, while we build on well-established information architecture like Zenodo, it is unlikely that the proposed metadata standard is definitive. Community adoption can reveal areas of further improvement. Furthermore, at the time of writing, dedicated indexing systems for FAIR theory are non-existent. Using the Zenodo search function and submitting theories to the "FAIR Theory Community" on Zenodo can help overcome this limitation in the short term.

Another limitation is the learning curve associated with tools like Git and Zenodo. The `theorytools` R-package mitigates this limitation by automating key steps in the process. Moreover, the initial investment in time can be offset by long-term productivity gains and increased impact of FAIR theory. One barrier to adopting FAIR theory is cultural resistance to sharing and modifying theories, also known as the "toothbrush problem". Education might help address this limitation; with this in mind, we are developing open educational materials on theory development.

A limitation of scope is that FAIR theory does not directly resolve problems related to strategic ambiguity (Frankenhuis et al., 2023) and lack of theory formalization (Robinaugh et al., 2021). However, our work does establish a framework that allows for and promotes the formalization of theories. The example of the empirical cycle demonstrates how FAIR principles can guide theory formalization and foster cumulative progress. Another limitation of scope is that FAIR theory does not resolve other related issues in psychology, such as the measurement crisis (Bringmann, Elmer, & Eronen, 2022) and lack of standardized ontologies for psychological constructs (Bosco et al., 2017). However, our work here provides a template for addressing such challenges, and any advancements in the areas of measurement and ontology will serve to amplify the value of FAIR theories, particularly when such resources are cross-referenced in the metadata (e.g., on Zenodo).

Future Directions

One issue that intersects with FAIR theory is the measurement and operationalization of psychological constructs. Aside from the aforementioned "theory crisis", there has been talk of a "measurement crisis": it is not always clear how theoretical constructs are operationalized, and many existing instruments have poor psychometric properties (Bringmann et al., 2022). Additionally, the "jingle-jangle" fallacy is prevalent in psychology: the same term is often used for distinct constructs, and conversely, different terms are used to refer to the same construct. FAIR theory can help address the measurement crisis: since theories can reference other theories and resources, it is possible to extend a structural theory with a theory of measurement.

Conclusion

FAIR theory is a major step forward towards more transparent, collaborative, and efficient theory construction. It provides much-needed open science methods for the inductive phase of the empirical cycle, closing a critical gap in the scientific process. FAIR theory makes theory more tangible, enabling scholars to incorporate it in their day-to-day workflows in order to derive hypotheses, select control variables, and contribute new data-driven insights. This paves the way for more theory-driven scholarship, and accelerates cumulative knowledge acquisition in the psychology, other social sciences, and beyond.

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