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Research Hardware Definition

A report by the RDA FAIR4RH Interest Group, Subgroup 1: FAIR4RH-Definition

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Title: Research Hardware Definition

Abstract:
"Research Hardware is a physical object developed as part of or for a research process." This definition is proposed after reviewing and discussing the literature about the related concept of open (source) hardware, scientific hardware, other hardware in research, and related research outputs. We also discuss the relation between research hardware and its package of (digital) assets that may include hardware design files, software, documentation, and branding. This definition includes research hardware of any complexity, independently of the quality of its documentation package or from its initial or current purpose. In many cases, projects should ascertain objects as research hardware at their own discretion.

Contributions to the United Nations Sustainable Development Goals (SDG): Goals directly covered in this document: 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption, and Production), 17 (Partnership for the Goals). Goals indirectly covered by promoting open research hardware: 3 (Good Health and Well-being), 4 (Quality Education), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 10 (Reduced Inequalities), 11 (Sustainable Cities and Communities), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land).

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Executive summary

This publication documents the work of the Research Hardware definition subgroup of the FAIR4RH (FAIR for Research Hardware) RDA (Research Data Alliance) interest group. The following definition is proposed:

Research Hardware is a physical object developed as part of or for a research process.

Other hardware that is used in research but has not been developed as part of or for a for this research process should be called *"hardware in research"*.

A wide range and number of hardware has been developed in research and some may have lost their dedication to research.

Research hardware can result from research outside academia, for instance as the result of citizen science, commercial or military research. In all these cases, we may speak of research hardware, and users of this definition should ascertain objects as research hardware at their own discretion.

Hardware is often specified by design files and enhanced by further text documentation. Some research hardware is interdependent with software, requires firmware, and/or other hardware to function. These (digital or analog) objects are called assets, the collection of these assets is referred to as the hardware documentation package.

In contrast to many hardware concepts referenced in this document, this research hardware definition does not require the existence of a documentation package, open licensing, and quality aspects like reusability. These notions are considered part of the FAIR principles for Research Hardware and are outside the scope of this document..

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Introduction and methodology

This chapter introduces the definition and its extension and lays out the methods of our work.

Our motivation

As stated in our charter (2022), “We believe that adapting and expanding the FAIR principles for the domain of research hardware can facilitate and improve hardware dissemination practices”. Very early on, we realized that we first needed a clear definition of “research hardware” to avoid misunderstanding and allow for better collaboration which is in line with the United Nations Sustainable Development Goal (UN SDG) 17 (Partnership for the Goals). This work is therefore a necessary preparatory step into our future work on the Adaptation of FAIR principles for research hardware.

Furthermore, a clear definition of “research hardware” and improved collaboration can ultimately contribute to an improved, sustainable production, use and re-use of such hardware, thus contributing to UN SDG 9 (Industry, Innovation and Infrastructure) and UN SDG 12 (Responsible Consumption and Production).

Scope

The main aim of the FAIR4RH RDA IG (FAIR principles for Research Hardware Research Data Alliance Interest Group) is to assess how FAIR principles (Wilkinson et al., 2016) can be applied to research hardware. Use cases of research hardware (RH) are likely to include (but are not limited to) commercial, military, and academic research, as well as citizen science. The proposed definition can be applied outside the academic research domain.

Definition

Research Hardware is a physical object developed as part of or for a research process.

Methodology

In order to construct this document, we performed a review of RH in literature, and discussed our definition, based on practical use cases.

In our literature review, no publications with a focus on research hardware emerged, but collected information related to “scientific hardware”, “free hardware”, and “open (source) hardware”, which are related concepts detailed later in this document. The aims of this overview were: (1) to find relevant quotes around RH and relevant terms (*e.g.*, “open hardware for research/science”) and (2) to provide proper factors that should be taken into account for suggesting a research hardware definition. The integrative overview of selected references is neither exhaustive nor a systematic review, but rather a detailed overview performed on selected literature, determined by the relevant keywords and snowballing method. Snowballing procedure starts with an initial set of references which is then increased by both forward and backward search procedures (Sayers, 2008; Wohlin, 2014); it is based on ideas of effective review initially presented in (Webster & Watson, 2002). A tentative set of papers was determined from (Miljković et al., 2022) which used a similar approach in their review. Then, the identified literature was expanded with recommendations from members of the FAIR4RH group and other contributors. This is not a result of a completely exhaustive search procedure as proposed in (Webster & Watson, 2002), but we strived to determine as many relevant references as possible.

In order to determine RH use cases where a definition may apply, we documented known usage scenarios and searched the web for other examples. Several WWW search engines were utilized, video content platforms, forums, and blogs, popular within the community (Paffhausen, 2019). Hardware documentation assets can be found on the GitHub platform, Sourceforge, Google Code (Corsini et al., 2020; Söderberg, 2011), the Open Science Framework, or on Gitlab instances (Colomb et al., 2024). Makers of free and open-source hardware for science are advised to share their designs for improved findability on as many places as possible. Examples include SourceForge, NIH 3D Print exchange, Ultimaker YouMagine, or MyMiniFactory repositories of open-source companies (Oberloier & Pearce, 2017). We limited our investigation to information related to definition work.

The first part of the document summarizes the current state of the literature and presents use cases that we used as examples and edge cases. In the second part of the document, we report discussions about specific aspects that were particularly interesting or controversial, either in the literature or within our group. This second part also discusses the scope of the definitions, similarities, and differences to the related concepts of scientific hardware, open hardware (OH), related research output and hardware in research, as well as different qualities of research hardware and its documentation package.

Overview of current state of knowledge regarding research hardware

Existing definitions related to the research hardware

Table 1, includes an overview of definitions found in literature and on the Internet. All definitions are inspected for four parts that were identified as relevant for RH definition. Three parts: (1) physical component, (2) design files, and (3) documentation are directly relevant for the RH definition, while the fourth part (openness) is not required for RH definition, but it is recognized as important in makers communities and in scientific research that follows open science practices. Although the presented overview of proposed definitions contains either open or general definitions of hardware found through performed search, RH can be both open (as in freely replicated or reused), as well as closed (*e.g.*, patented research hardware).

Table 1, Comparison of the proposed RH definition (highlighted in grey) with existing definitions.

Term defined	**Source**	**Physical components**	**Design files**	**Documentation**	**Openness**
Research hardware [proposed definition]	RDA	Yes	Yes	Yes	Not required
Open Source Hardware	(*OSHW - Definition of Free Cultural Works*, n.d.)	Yes	Yes	Not mentioned	Required
Open Source hardware	(Acosta, 2009)	No	Yes	Not mentioned	Required
Open Source Hardware	(Bonvoisin et al., 2020)	Yes	Not mentioned	Not mentioned	Required
Open source hardware	(Hannig & Teich, 2021)	Yes	Yes	Yes	Required
open source hardware	(Söderberg, 2011)	Yes	Yes	Yes	Required
Open source hardware	(DIN SPEC 3105-1, n.d.)	Not mentioned	Yes	Yes	Required
Open Science hardware	GOSH (2016)	Yes	Yes	Not mentioned	Required

Term defined	Source	Physical components	Design files	Documentation	Openness
Open science hardware	(Kera, 2017)	Yes	Not mentioned	Not mentioned	Required
Open hardware	(Parker et al., 2021)	Yes	Not mentioned	Not mentioned	Required
Open hardware	(Rakitin & Markova, 2022)	No	Yes	Not mentioned	Required
Open hardware	(Ackerman, 2008)	Yes	Yes	Yes	Required
Open hardware	(Kauttu & Murillo, 2017)	Not mentioned	Not mentioned	Not mentioned	Not required
Open hardware	(opensource.com community, n.d.)	Yes	Yes	Not mentioned	Required
Hardware Freedom	(*4xFreedoms | Open Source Hardware and Design Alliance*, 2012)	Yes	Yes	Not mentioned	Required
Hardware	(Hannig & Teich, 2021)	Yes	Not mentioned	Not mentioned	Not mentioned
Free Hardware	(Stallman, n.d.)	Yes	Yes	Not mentioned	Required
Documentation	(Ayass & Serrano, 2012)	Yes	Yes	Yes	Required

The proposed research hardware definition explanation is partly inspired, created, and modified from the summary report on the Controversial Discussion to define research software (Gruenpeter et al., 2021) and the FAIR principles for research software (Chue Hong et al., 2021).

> *"Research Software includes source code files, algorithms, scripts, computational workflows and executables that were created during the research process or for a research purpose. Software components (e.g., operating systems, libraries, dependencies, packages, scripts, etc.) that are used for research but were not created during or with a clear research intent should be considered software in research and not Research Software. This differentiation may vary between disciplines. The minimal requirement for achieving computational reproducibility is that all the computational components (Research Software, software used in*

research, documentation and hardware) used during the research are identified, described, and made accessible to the extent that is possible."

The GOSH (Gathering for Open Science Hardware) definition of open science hardware in the GOSH manifesto (2016) is widely used and represents a case where "biological reagents" are included:

"*Open Science Hardware (OScH) refers to any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone. It includes standard lab equipment as well as auxiliary materials, such as sensors, biological reagents, analog and digital electronic components. Given that proprietary "black box" instrumentation cannot be fully inspected or customized, and can be unreasonably difficult and expensive to obtain and maintain, we believe that scientific hardware design should be open to allow for the exercise of these basic freedoms.*",

Other relevant definitions from the literature that are present in Table 1 are provided hereafter.

Open Source Hardware Definition v1.0 (*OSHW - Definition of Free Cultural Works*, n.d.):

"Open Source Hardware (OSHW) is a term for tangible artifacts -- machines, devices, or other physical things -- whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things. This definition is intended to help provide guidelines for the development and evaluation of licenses for Open Source Hardware. Hardware is different from software in that physical resources must always be committed for the creation of physical goods. Accordingly, persons or companies producing items ("products") under an OSHW license have an obligation to make it clear that such products are not manufactured, sold, warrantied, or otherwise sanctioned by the original designer and also not to make use of any trademarks owned by the original designer."

Acosta (Acosta, 2009) used the definition derived from literature and Internet sources dedicated to OH in which OH is not considered physical artifact, but hardware design:

"*The general consensus is that Open Source hardware is electronic hardware design that is "freely available under one of the legally binding recognized open source licenses". The open source hardware includes schematics, diagrams and design rules that can be used, studied and modified without restriction and can be copied and redistributed in modified or unmodified form either without restriction,or with minimal restrictions only to ensure that further recipients can do the same.*"

Bonvoisin and co-authors (Bonvoisin et al., 2020) defined OH as:

"*Open Source Hardware (OSH), often simply referred to as Open Hardware, is* *an emergent phenomenon applying to physical products the alternative approach to traditional intellectual property (IP) protection that has been developed in Open Source Software (OSS) through decades of practice.*"

Hannig & Teich, (Hannig & Teich, 2021) used the following OH definition:

"*Open source hardware (OSH) refers to physical components generated by a decentralized design and development model encouraging open collaboration. OSH is an analogy to open source software. OSH usually intends that information about the hardware is readily identifiable so that others can make it. OSH refers to hardware designs whose specifications, construction instructions, and documentation can be publicly accessed, modified, and used by others. Hardware generally can refer to everything that can be built.*"

Söderberg (Söderberg, 2011) underlines the importance of source code and the aesthetic value:

"*The open source hardware consists of some items to protect: (1) the source code for electronics (e.g.: VHDL or Verilog source codes), (2) the source code for associated softwares (e.g.: development tools, SDK, etc.), (3) the schematics, the design files and the technical drawings (what we named "hardware design"), (4) the aesthetic value, (5) the documentations, and (6) the brands.*"

DIN (Deutsches Institut für Normung) SPEC 3105 standard defines open hardware (DIN SPEC 3105-1, n.d.) mainly in relation to hardware openness while it does not recognize design files and documentation as separate digital assets:

"Open source hardware (OSH) is hardware for which a free right of any use is granted to the general public and whose technical documentation is completely available and freely accessible on the internet."

Kera (Kera, 2017) used the following OH property to define OH:

"*Open science hardware (OSH) presents an alternative to proprietary, standardized (above 109 ISO norms), and often expensive laboratory instruments.*"

Science and Technology Innovation Program (Wilson Center) (Parker et al., 2021) OH definition:

"*Open hardware is physical—typically made from functional chunks of metal and plastic—but the way it is developed, shared, and used generates a social infrastructure that has great potential to respond to societal challenges.*"

Rakitin & Markova (Rakitin & Markova, 2022) defined OH as design files by excluding physical parts from the OH definition:

"*"Open source hardware" or "Open hardware" specifies the physical real object's* *design, which specifications are licensed in a way which that object can be changed, modified and distributed by everyone. "Open hardware" is a composition of design principles and legal matters and does not refer to a certain object or type. Therefore, the "Open hardware" can point to anything - such as cars, tables, electronics, or even buildings.*"

Ackerman (Ackerman, 2008) used the following definition for the TARP (Tucson Amateur Packet Radio) OH license where they emphasized that the documentation includes design:

"*Open Hardware is a thing – a physical artifact, either electrical or mechanical – whose design information is available to, and usable by, the public in a way that allows anyone to make, modify, distribute, and use that thing. In this preface, design information is called "documentation" and things created from it are called "products."*"

Murillo & Kauttu (Kauttu & Murillo, 2017) adopted the text from (Edwards, 2010), which we consider rather abstract:

"*For our purposes, OH will be described as a highly adaptable platform to integrate present and future "knowledge infrastructures," which represent "robust networks of [scientists], artefacts, and institutions that generate, share, and maintain specific knowledge" in various professional and academic fields.*"

The opensource.com community defines OH in (opensource.com community, n.d.):

"*"Open hardware," or "open source hardware," refers to the design specifications of a physical object which are licensed in such a way that said object can be studied, modified, created, and distributed by anyone. "Open hardware" is a set of design principles and legal practices, not a specific type of object. The term can therefore refer to any number of objects—like automobiles, chairs, computers, robots, or even houses. Like open source software, the "source code" for open hardware—schematics, blueprints, logic designs, Computer Aided Design (CAD) drawings or files, etc.—is available for modification or enhancement by anyone under permissive licenses.*"

Powell, (A. Powell, 2012) used the definition introduced by Open Hardware and Design Alliance in 2009 (*4xFreedoms | Open Source Hardware and Design Alliance*, 2012) :

"*Hardware Freedom 0. The freedom to use the device for any purpose; Hardware Freedom 1. The freedom to study how the device works and change it to make it to do what you wish. Access to the complete design is precondition to this; Hardware Freedom 2. The freedom to redistribute the device and/or design (remanufacture); Freedom 3. The freedom to improve the device and/or design, and release your improvements (and modified versions in general) to the public, so that the whole community benefits. Access to the complete design is precondition to this. (Open Hardware and Design Alliance, 2009).*"

The OH definition proposed by Hannig and Teich incorporates general hardware definition (Hannig & Teich, 2021), where by “everything” they probably refer to “physical objects”:

> “*Hardware generally can refer to everything that can be built.*”

Free Software Foundation defines free hardware as free-design hardware by focusing on the four essential software freedoms that can not be applied directly to the physical object (Stallman, n.d.):

> “*Applying the same concept directly to hardware, free hardware means hardware that users are free to use and to copy and redistribute with or without changes. However, there are no copiers for hardware, aside from keys, DNA, and plastic objects' exterior shapes. Most hardware is made by fabrication from some sort of design. The design comes before the hardware… By contrast, hardware is a physical structure and its physicality is crucial. While the hardware's design might be represented as data, in some cases even as a program, the design is not the hardware.*”

Ayass & Serrano (Ayass & Serrano, 2012) defined OH for the purpose of introduction of CERN (The European Organization for Nuclear Research) OH licenses. Their definition has an extensive list of terms that can be considered documentation including designs:

> “*Documentation” means schematic diagrams, designs, circuit or circuit board layouts, mechanical drawings, flow charts and descriptive text, and other explanatory material that is explicitly stated as being made available under the conditions of this Licence. The Documentation may be in any medium, including but not limited to computer files and representations on paper, film, or any other media. “Product” means either an entire, or any part of, a device built using the Documentation or the modified Documentation.*”

Identified RH terms in literature

The listing of terms in Table 2 is neither exhaustive nor complete and should serve only to give relevant insights from the literature which is mainly focused on OH for science.

The terms identified were grouped into the following categories (Table 2): (1) equipment, (2) instrument, (3) hardware, (4) tool, (5) design, (6) device, (7) physical object, (8) product, (9) parts/building blocks, (10) platform, and (11) miscellaneous (containing prototype, infrastructure, sensor project, and lab set-up). The categorization in parts resembles the topics identified in the literature and presented in the following subchapter, except for the quality topic. Namely, categories 5 (design) and 7 (physical object) specifically emphasize the question of physical and digital RH components. The purpose is emphasized in the equipment, instrument, tool, product, platform, and miscellaneous groups, whereas parts/building blocks are highlighted in a separate category. It is interesting to note that research did not appear in the following categories: (5) design, (7) physical object, (8) product, (10) platform, and (11) miscellaneous, while the majority of references used (1) equipment and (5) design.

Table 2, List of terms identified in available literature in relation to the research hardware. All reviewed references and terms are used in the context of open hardware. This is not a result of an in-detail and exhaustive text mining procedure, but a result of manual selection of relevant and common terms from literature. Therefore, the number of references could be analyzed with the grain of salt. The identified terms are either equivalent (==) or present a subset (⊆) of Research Hardware (RH).

Grouping terms	**Term**	**Number of references**	**RH relation**	**Number of references**
equipment	scientific equipment, science equipment	8	⊆	13
	research equipment	3	==	
	highly specialized equipment	1	⊆	
	customized equipment	1	⊆	
	physical equipment	1	⊆	
	laboratory equipment	1	⊆	
	hardware equipment	1	⊆	
	equipment	7	⊆	
instrument	scientific instrument, scientific instrumentation, science instrument	8	⊆	9
	research instrumentation/instrument, research-grade scientific instruments	5	⊆	
	laboratory instrument	1	⊆	
	instrument / instrumentation	2	⊆	
hardware	scientific hardware, hardware for science, science hardware, hardware in science	13	⊆	13
	electronic hardware	2	⊆	
	research hardware, hardware resulting from research, hardware for research	3	==	
tool	highly customized low-volume tools	1	⊆	12
	laboratory tool	1	⊆	

Grouping terms	Term	Number of references	RH relation	Number of references
	scientific tool, tool for science, science tool, scientific tool	7	⊆	
	research tool	2	==	
	common tool	1	⊆	
	tool	4	⊆	
design	manufacturing designs	1	⊆	17
	scientific design	2	⊆	
	scientific hardware design	1	⊆	
	electronic design / design schematics / design scheme	4	⊆	
	hardware design	6	⊆	
	physical design	1	⊆	
	open (source) design	3	⊆	
	instrumentation design	1	⊆	
	electronic hardware design	1	⊆	
	design files for hardware	2	⊆	
	hardware design and implementations	1	⊆	
	digital design of physical object / design of material object	2	⊆	
device	scientific device	2	⊆	11
	mechanical and electronic devices	2	⊆	
	research device	1	⊆	
	machine	3	⊆	
	device	7	⊆	
physical object	physical embodiment of a circuit board	1	⊆	6
	physical artefact and technologies	1	⊆	
	physical artifact / artifact	3	⊆	
	physical sample	2	⊆	

Grouping terms	Term	Number of references	RH relation	Number of references
	physical implementation of the board	1	⊆	
	functional object	1	⊆	
product	physical product	3	⊆	8
	tangible product	2	⊆	
	electronic product	1	⊆	
	product manufactured from the documentation	1	⊆	
	product	4	⊆	
parts/building blocks	physical component	1	⊆	6
	custom component	1	⊆	
	component	2	⊆	
	part	1	⊆	
	item	1	⊆	
	Research equipment, spare parts, and consumables	1	==	
	reagent	1	⊆	
platform	scientific platform	1	⊆	3
	platform	2	⊆	
miscellaneous	prototype	1	⊆	3
	infrastructure	1	⊆	
	sensor project	1	⊆	
	lab set-up	1	⊆	

Research hardware use cases

The goal of this section is to review collected examples/use cases that contributed to the definition of the research hardware. Specific attention is paid to edge cases which are further elaborated in the Discussion section.

Research is conducted in several parts of our society. Dedicated hardware is reused or created for particular use cases. There are interactions or collaborations between the academic community, commercial industry, military organizations, NGOs, public services, and citizen scientists.

The Subgroup 1 on FAIR4RH-Definition reached out to different stakeholders and individuals to attract diverse contributions about research hardware use cases from around the globe including users and practitioners from low and moderate income countries. The list presented in Table 3 provides examples to illustrate the diversity of research hardware. It focuses on OH due to the difficulty assessing closed source documentation apart from patent databases.

Table 3, Overview of selected published research hardware / use cases. Abbreviations are HW - hardware, SW - software, GW - gateware, and Doc - documentation.

Reference(s)	**Research hardware**	**License**	**Repository**	**Area of application**	**Type of hardware**
Patent US7649160B2	digital holographic microscope	patented	none	Biology / physics	Mechanical, electrical, digital and optical parts with dedicated software required for operation
none	Transgenic drosophila	Material transfer agreement	Flybase	biology	Living organism
(Purser et al., 2020)	PlasPI marine camera	CERN OH v1.2	OSF	Marine Science	Mechanical, electrical, and optical parts with dedicated software required for operation
(Moritz et al., 2019)	Open source Magnetic Resonance Imaging (MRI) device (COSI, Cost–effective Open-Source Imaging)	CERN OH v1.2	GitHub	Healthcare technologies	Mechanical, electrical, software, and accessories
(Legenvre et al., 2020)	RISC-V instruction set integrated within a processor	BSD license and CC licenses for documentation	GitHub	General-purpose electronics, Computer science	Interface between software and hardware
(Read et al., 2021)	Inline monitor/tester for ventilators	HW: CERN OH v2 SR SW: GPL v3.0 Doc: CC0	GitHub	Healthcare technologies	Mechanical, electrical, software
(*Building Blocks for DC Energy Systems | The*	MPPT/PWM solar charge controllers and	HW: CERN OH v2 WR SW: Apache v2	GitHub	Electric power generation	Electrical, Electronic Software,

Reference(s)	Research hardware	License	Repository	Area of application	Type of hardware
Libre Solar Project, n.d.)	battery management systems				Mechanical
(Hill et al., 2019)	Audiomoth	HW: Creative Commons Attribution SW: MIT	GitHub	Biology	Electronic, Mechanical (case), Software
(Lipinski et al., 2011)	White Rabbit	HW: CERN OHL v1.x SW: GNU GPL v2 GW: No license	Gitlab (Open Hardware Repository)	Computer science, Laboratories	Electronic, Software, Gateware, Mechanical (case)
(Camprodon et al., 2019)	Smart Citizen Kit	HW: CERN OHL v1.2 SW: GNU GPL v3.0	GitHub	Environmental protection, Citizen science	Electronic, Software
(Carrasco-Escobar et al., 2020)	GORGAS tracker	GPL v3.0	GitHub	GPS tracking	Electronic, Mechanical (case), Software
(*Open Source Ultrasound*, n.d.)	un0rock/lit3rick ultrasound boards	HW: TAPR Open Hardware License v1.0 SW: GNU GPL v3.0+ Docs: CC BY-SA v3.0	GitHub	Ultrasound experiments	Electronic, Software Gateware
(Marzullo & Gage, 2012)	Spiker box	CC BY-SA, certified as open source hardware and for software commonly free MIT license	Website, Google drive, GitHub, scientific publications	Electrophysiological equipment (recording electrical potentials in humans and animals)	Electronic, Firmware, Software
(Ltd, n.d.)	RaspberryPi	For documentation various CC licenses, for software various free BSD, MIT, and GNU GPL, and hardware design is open without specific license (where design files of some parts are closed)	Website and GitHub	Single board computer with general purpose input output pins	Electronic, Firmware, Software, Documentation
(*Arduino - Home*, n.d.)	Arduino boards	Hardware is licensed by CC-BY SA and software with GNU GPL and GNU LGPL for software libraries	Website and GitHub	Microcontroller-based boards with programming environment and dedicated shields (add-ons)	Electronic, Firmware, Software
(Jones et al.,	RepRap	GNU Free	Website,	Self-replicating	Electronic,

Reference(s)	Research hardware	License	Repository	Area of application	Type of hardware
2011)	(Replicating Rapid-prototyper)	Documentation license for documentation, designs use different licenses (commonly GNU GPL and CC), the RepRap itself is licensed by GNU GPL	GitHub, and Thingiverse	manufacturing machine (3D printer)	Mechanical, Software, Documentation
(de Vos, 2021)	Plastic scanner	GPL-3.0 license	GitHub	Recycling, detector	Mechanical, electrical, software, and accessories

As can be seen in Table 3, research hardware is produced and used in a wide variety of research disciplines and applications. Besides the variety of licenses used to cover different parts of selected use cases (either specifically designed for OH or general purpose licenses such as CC licenses), we also see a variety of physical components and digital assets, in most cases containing a very detailed documentation.

Assets and hardware documentation package

When discussing the research hardware at hand and all possibly related objects, we needed a term to address such objects. The terms “documentation” or “source” are sometimes used, but may relate only to one sub-category of these related objects. We then considered the terms “artifacts” and “assets”. While “assets” have an economic connotation, we recognized that “artifacts” and especially “digital artifacts” are terms assigned to (sometimes) unwanted outputs in some communities (‘Digital Artifact’, 2024), or digital copies of analog objects in others (also virtual artifacts, (‘Virtual Artifact’, 2024)). The discussion resulted in “assets” to refer to these objects (see Fig. 2).

Discussion of concepts related to research hardware

Here in this chapter we first discuss long-standing concepts that were established before the proposed definition and how they relate to our work. From the literature review and discussions within FAIR4RH RDA interest group, we identified the following concepts: (1) scientific hardware, (2) OH hardware, (3) research output outside of scientific research, (4) hardware in research, (5) physical objects, (6) hardware in relation to software, (7) research hardware complexity, (8) research hardware quality, and (9) research hardware (re)purposing.

Scientific hardware

We found it useful to distinguish between research hardware and scientific hardware based on the available definitions of both, scientific and non-scientific research, and based on the relevant literature which addresses both. The main characteristic of scientific research is the scientific method, which acquires knowledge and finds solutions to research problems through systematic observations, predictions, and empirical testing (Gravetter & Forzano, 2018). Research, in general, acquires knowledge and evidence, but does not necessarily follow the aforementioned scientific method (*Application of Scientific and Non-Scientific Research - ACADEMIA*, n.d.). As depicted in Fig. 1, our approach assumes that research hardware is a special case of hardware in general, while scientific hardware is a subset of research hardware. An example of "hardware in research", which is a distinct concept, is detailed later. In general, research or scientific hardware may be publicly or privately funded, or both.

In the particular case of engineering, the research processes include ideation, specification, detailed design, and validation, as well as production activities, including manufacturing, inspection, assembly, testing, reuse of materials, components, products and waste (Clarkson & Eckert, 2005). The research carried out in engineering is usually collaborative creating a shared understanding by means of information exchange. From a cognitive point of view, it consists of problem solving and solution finding, but also deeper problem analysis such as problem finding.

Open source hardware

A relatively large number of available sources (Bonvoisin et al., 2020; Pearce, 2017; Serrano, 2017; Söderberg, 2011; Moritz et al., 2019; Li et al., 2017; Herrera, 2020; Murphy, 2020; Corsini et al., 2020; Miljković et al., 2022; Kauttu & Murillo, 2017; Bonvoisin & Mies, 2018) use the definition proposed by the Open Source Hardware Association (OSHWA): "The term Open Source Hardware (OSH) refers to a product whose design has been released to the public in such a way that anyone can make, modify, distribute, and use it" (*OSHW - Definition of Free Cultural Works*, n.d.), while other (Arancio et al., 2022; Kera, 2017) used the definition proposed by the Global Open Science Hardware Manifesto (2016), see also (Dosemagen et al., 2017; Murillo et al., 2017)] as hardware that can be used by anyone to "create, obtain, study, modify, distribute, use, and share (scientific instruments) designs". Open hardware has been described in a context of "collaborative design model" where Herrera emphasized the development aspect of OH (Herrera, 2020). Also, depending on the context, authors tend to use very narrow definitions, as in (Murillo et al., 2017) where the definition of OH was extended to the innovation platform as a potential business model. In (Bonvoisin et al., 2020), the authors explore the previous definitions for OH and conclude that it emerged around electronics, but that today it does not exclude mechanics and textiles. Regardless whether hardware relates to electronics, mechanics, textiles, or of any combination thereof, it can comprise both, digital design and physical embodiment. The digital aspects of OH are printed circuit board designs, photomask layouts, and mechanical assemblies where the complete documentation contains both text (*e.g.*, bill of materials and source code), as well as binary files (*e.g.*, circuit board layout) (Harnett, 2011). Other identified parts of OH include "(1) the source code for electronics (*e.g.*, VHDL or Verilog source codes), (2) the source code for associated softwares (*e.g.* development tools, SDK), (3) the schematics, the design files and the technical drawings (what we named "hardware design"), (4) the aesthetic value, (5) the documentations, and (6) the brands." (Viseur, 2012). Similar lists have been reported elsewhere, for example in (Pearce, 2016) "the bill of materials, schematics, assembly instructions, and procedures needed to fabricate a digital replica of the original", and in (Miljković et al., 2022) where OH digital form includes physical design, software, and documentation.

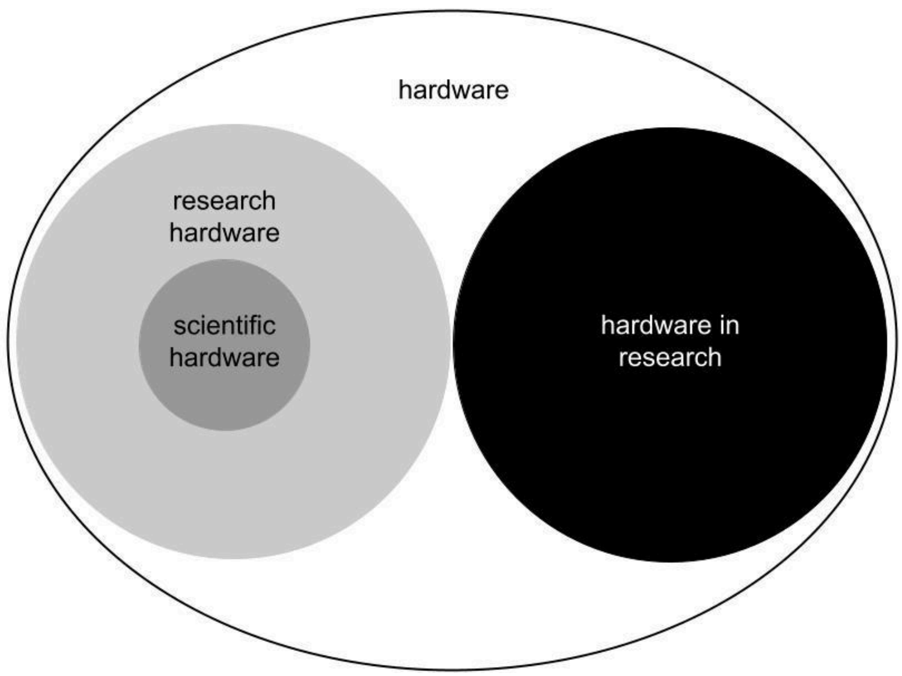

Figure 1, Graphical representation of intersections of possible levels of hardware (hardware in general, research hardware, and scientific hardware). Some general hardware may be used in research but not exclusively and without research purpose. Open hardware is not displayed here as it relates to licensing. Some research hardware may be interacting with other objects.

Research hardware does not necessarily include OH, but the majority of reviewed literature is organized around OH for science. Although researchers and scientists may be primarily interested in OH products and its open dissemination (Li et al., 2017; Serrano, 2017) due to the long-standing Open Science ideas, openness does not necessarily apply to research hardware or hardware in general. As mentioned earlier, OH definitions are mainly concerned about openness and the digital assets of hardware that could be shared via the Internet. However, since hardware is made from atoms (Svorc & Katz, 2019) and cannot be shared digitally, only assets related to (open) research hardware can be made openly available. In terms of openness, different levels of design and process availability have also been discussed, such as closed hardware, open interface hardware, open design hardware, and open implementation (McNamara, 2007), which are all related to freedoms derived from the free software world. The proposed RH definition recognizes possible interrelations with software, especially firmware, which is emphasized in Fig. 2.

Research output

The equipment or hardware used for research could be both, the result of, and the means for (further) research. Acknowledging research hardware as a research result – similar to research data and software – enables a more comprehensive research assessment. To this day, the majority of hardware has been qualified and produced by commercial companies and has not been part of discussions as research output. However, the growing trend towards research-led development of bespoke hardware, together with the growing interest from the Open Hardware community, is challenging the status quo.

Hardware in research

Hardware that is used during the research process but is not dedicated to research is termed “hardware in research”. Such a definition is beneficial to distinguish between several classes of hardware as showcased in Fig. 1. A distinction based on dedication has also been made in the research software definition proposed by the FAIR4RS WG (Chue Hong et al., 2021) that discerns between research software and software in research. Similarly, the FDA (Food and Drug Administration) in the USA made differentiation between software in medical devices and software as a medical device (Health, 2020). We acknowledge that this differentiation may vary among disciplines.

Research hardware attributes

Physical objects

A definition of OH by Hannig and Teich (Hannig & Teich, 2021) incorporates a general hardware definition (“Hardware generally can refer to everything that can be built.”). Hardware is not just digital design, as it has been suggested in some definitions of OH (Acosta, 2009; Rakitin & Markova, 2022; Stallman, n.d.), but requires atoms (Svorc & Katz, 2019), so the physical aspect must be part of the RH definition.

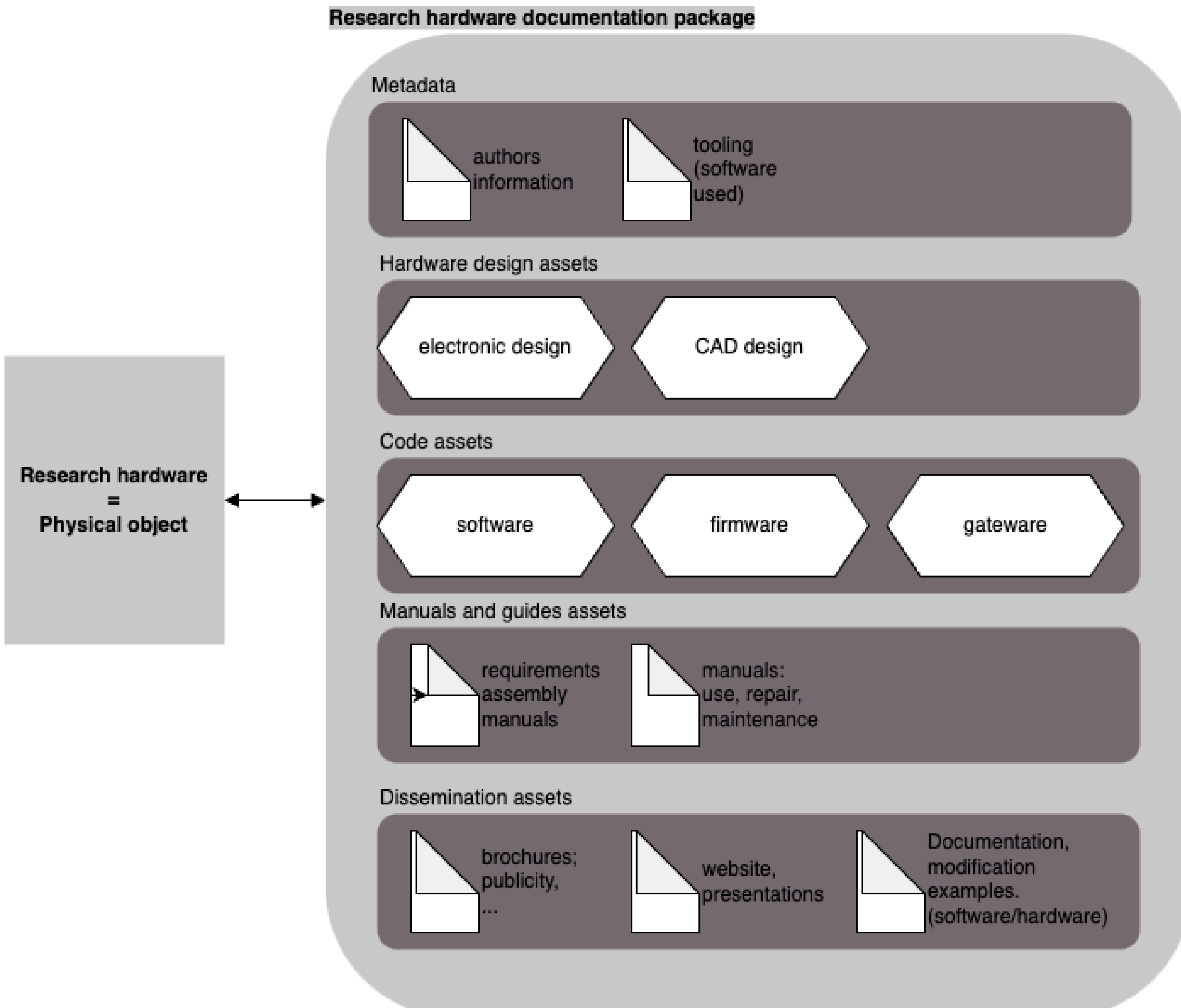

Fig. 2 Relation between the Research hardware which refers to the physical object, and its digital or analog assets. These latter different related objects (metadata, design files, code, manuals and guides, as well as dissemination products), which are often but not always in a digital form, are called assets. The assets can be bundled into a documentation package, and they are provisional as most hardware documentation packages do not contain all types of assets.

While RH does not require any documentation to exist, there is a strong link between the physical objects and its documentation package in research hardware, as the latter can be shared more easily and published as well. Identified parts of RH documentation include "(1) the source code for electronics (e.g., VHDL or Verilog source codes), (2) the source code for associated software and firmware (e.g. development tools, SDK, etc.), (3) the schematics, the design files and the technical drawings (what we named "hardware design"), (4) the aesthetic value, (5) the documentation, and (6) the brands." (Viseur, 2012). Similar lists have been reported elsewhere, for example in (Pearce, 2016)): "the bill of materials, schematics, assembly instructions, and procedures needed to fabricate a digital replica of the original" and in (Miljković et al., 2022) where OH digital form includes physical design, software, and documentation. Therefore, one important aspect of research hardware is that it *often* links to other (possibly digital) assets, as further detailed in the next sections.

Hardware in relation to software

Many resources use the analogy between open software and hardware (Ackerman, 2008; Bonvoisin et al., 2020; Dosemagen et al., 2017; Harnett, 2011; Miljković et al., 2022; Murphy, 2020; Pearce, 2012, 2016, 2017; A. Powell, 2012; Rubow, 2008; Serrano, 2017; Söderberg, 2011; Viseur, 2012). This analogy originates, among other factors, from the license definition, as OH licenses are derived directly from free and open-source software licenses that arose around copyright concepts (Ackerman, 2008) and by other practices inherited from the Free Software Foundation. A corresponding analogy is also incorporated in the OSHWA definition (*OSHW - Definition of Free Cultural Works*, n.d.). In addition, tools used for software development were adopted and adapted for hardware such as version tracking (*e.g.*, Git, Subversion, and Mercurial) (Harnett, 2011) while other hardware specific tools emerged from the software community to serve the needs of the makers community (*e.g.*, GitBuilding, Hardocs, DocuBricks, and Wikifactory) (Bonvoisin et al., 2020; Colomb et al., 2024).

Software, firmware, and other code loaded into programmable devices are excluded from the OH licenses such as TARP and CERN (the European Organization for Nuclear Research) OH due to the legal obstacles (Ackerman, 2008; Ayass & Serrano, 2012), but such code could be covered by the research hardware definition as being essential for the hardware function. In support of this claim: (1) publicly open review process of TARP license resulted in developers seeking for a unique license for hardware and dependable software (Ackerman, 2008) which was not fulfilled due to the legal reasons in creating such license (similar statement can be found in (Li et al., 2017): “The design files released should include all hardware design and software code”) and (2) OSHWA certification incorporates documentation, software, and physical design (*OSHWA Certification Process*, n.d.). A similar analogy is used for the collaborative design model that is translated from software to the hardware domain (Moritz et al., 2019).

Firmware is a specific type of software often needed to run hardware. It is in such a close relation to the hardware (Tan et al., 2017) that both hardware and firmware are only useful in conjunction (and mutually dependent, for instance in terms of energy consumption (Pohl et al., 2021)). The National Institute of Standards and Technology in the USA defines firmware as a software program and data stored in hardware (M. Powell et al., 2022), it is a subclass of software (*Gateware.Org - Definition of Gateware*, n.d.). ISO/IEC/IEEE International Standard 24765-2010 (‘ISO/IEC/IEEE International Standard - Systems and Software Engineering – Vocabulary’, 2010) defines firmware as a “combination of a hardware device and computer instructions or computer data that reside as read-only software on the hardware device”. The borderline between hardware and software nowadays is less apparent than ever before (Serrano, 2017). However, since firmware does not represent a physical object, we therefore use the term “asset” to refer to firmware and not classify it as research hardware.

While firmware represents executable computer code, there is also “gateware” closely related to hardware (*Gateware.Org - Definition of Gateware*, n.d.). Gateware can be used to produce a specific hardware design or to reconfigure specialized digital devices to emulate the hardware design. Some references define gateware as an entirely different entity from the firmware as above, while others define gateware as a type of firmware (Stallman, n.d.). Programming files for FPGA (Field Programmable Gate Arrays) and HDL (Hardware Description Languages) running in FPGA are both considered as gateware (*Gateware.Org - Definition of Gateware*, n.d.; Serrano, 2017) or firmware (Stallman, n.d.).

We also discussed whether or not a processor instruction set architecture represents an integral part of the research hardware and whether or not it should be covered by the RH definition. In the case of RISC-V (free instruction set architecture/design within the processor), an instruction set architecture is essential for microcontroller operation and it can be defined as an *interface* between hardware and software *within the processor* (Legenvre et al., 2020; Waterman, 2016). Other sources have classified the RISC-V instruction set architecture as a *software* that enables microprocessor design (Bonvoisin et al., 2020), some processor core designs implementing RISC-Vs have been explored in the sense of the open source hardware example (Herrera, 2020). Further, Hannig and Teich referred to RISC-V as an open source hardware solution (Hannig & Teich, 2021), probably in the sense of the building block which is commonly used for hardware components. Note that an Instruction Set Architecture (ISA) is mainly seen as an interface specification (Asanović & Patterson, 2014) and not an implementation. As such it is more of an integral part of hardware documentation or specification than actual hardware. ISA is also a software specification. In conclusion, whether defined as a software or hardware-software interface, an Instruction Set Architecture (ISA) is a building block of some research hardware.

This publication recognizes the complex interdependencies of software and other relevant “interfaces” (*e.g.*, firmware, gateware, instruction set architecture) required to operate selected research hardware. We consider such required technology as interrelated to our definition of research hardware as depicted in Fig. 2.

Research hardware complexity

The scales of research hardware vary tremendously from small accessories and building blocks to very complex machines being either of low or high complexity in its design, size, and dependencies presenting either standard or custom equipment, “physical artifact” or “product” (Ackerman, 2008; Acosta, 2009; Bonvoisin et al., 2018, 2020; Bonvoisin & Mies, 2018; Brazil, 2018; Corsini et al., 2020; Hannig & Teich, 2021; Miljković et al., 2022; Moritz et al., 2019; Oberloier & Pearce, 2017; Pearce, 2017). The range of hardware complexity has been investigated mostly for OH. The current literature has not covered RH in such detail. Only the GOSH definition of open science hardware (2016) addresses “any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone” which incorporates not just specific laboratory equipment, but also supplementary materials (*e.g.*, reagents, sensors).

Discussions within the community raised further questions: To what extent can hardware be defined as supplementary material to research hardware (as in “part of”) and to what extent as a unique and separate part or tool? Is there any level of complexity in scales and building blocks that should be incorporated in the definition? Is the RH functioning and utilitarian nature important for an item to be identified as separate and independent RH?

The proposed definition does not specify the building blocks and does not limit RH component definition. Depending on the purpose and discipline, building blocks can be considered RH components.

Research hardware quality

Jenny Melloy, researcher at the University of Cambridge, UK, stated that the main difference between open hardware in the makers community and in the sciences is the need for “quality assurance, adherence to standards, calibration and reproducibility” [39]. The repeatability and replicability claims are further confirmed as important factors in scientific methodology in (Harnett, 2011; Oberloier & Pearce, 2017; Pearce, 2017) together with maintenance, upgrading, repair, recycling, safety, risk-free operation, and end-of-life disassembly being part of the available DIN SPEC 3105-1 OH standard (DIN SPEC 3105-1, n.d.). This is a rather important feature of research hardware and there are repositories such as NIH 3D Print Exchange (U.S. Department of Health and Human Services — National Institutes of Health) that emphasize that 3D-printable models (of research hardware) should be both scientifically accurate and applicable in science [45]. Moreover, it has been stated that product innovation is more intense for scientific equipment than for other sectors of application (Arancio et al., 2022), making research hardware probably to a greater extent vulnerable to interoperability and reusability. RH should be extended by validation and verification reports to ensure quality required by the respective community.

The proposed definition does not limit the purpose, creators, and (quality) standards application to research hardware – it is left to communities to apply it to their needs and practices.

Research hardware (re)purposing

We decided to follow the relations presented in Fig. 1, so we used existing literature on OH and hardware for science, to identify possible important topic(s) related to research hardware such as purpose and customization. RH can have multiple purposes (Pearce, 2016), for example, research, science communication, politics, and leisure (art) (Kera, 2017). RH can be exercised and developed by people with diverse backgrounds (*e.g.*, students, researchers, consumers, hackers, hobbyists, and users) (Kauttu & Murillo, 2017; Moritz et al., 2019; A. Powell, 2012). The actors / designers / users of research hardware could be researchers as well as citizens (*e.g.*, citizen scientists, artists, and enthusiasts) (Arancio et al., 2022; Kauttu & Murillo, 2017; Kera, 2017; Parker et al., 2021). A relatively recent report (Parker et al., 2021) emphasized the role of OH, where open source microscopes could be used for both diagnostics and research.

In (Rakitin & Markova, 2022), one of the identified OH applications is "in support of research". Further, in (Pearce, 2014) "scientific equipment", "open-source designed for lab equipment", and "scientific hardware/tools" developed by researchers are discussed, though research hardware is not mentioned. In a similar manner, Kera (Kera, 2015) refers to customizable laboratory equipment for experimental research. "Hardware in science" has been described as a both "research product" and "scientific result" (Parker et al., 2021). We consider research hardware to be primarily used for research purposes, but this shall not exclude other applications, similar to devices that are "built primarily for educational purposes, rather than research" (Brazil, 2018).

The group also discussed how hardware is developed during research and for research. Sampling physical or biological material is considered a scientific activity that falls under development and the resulting hardware can be utilized in further research. The proposed definition covers these aspects. We emphasize that customization and repurposing of hardware is common in the research process, and a research hardware definition should cover existing customization practices. As stated before, practices are specific to different communities and disciplines who should apply the definition according to their needs.

Conclusions

The FAIR4RH IG examined case studies that highlight key aspects and issues in research hardware creation, deployment, and dissemination in order to provide a definition that would benefit the application of FAIR principles to research hardware. The proposed definition includes both the physical component and (where needed or appropriate) the documentation package, which itself could include firmware and other software types, design files and branding.

While the proposed definition does not require openness of research hardware documentation, the concept of open hardware design is expected to benefit society. It likely improves global knowledge sharing and may benefit sustainable manufacturing (Undheim, n.d.).

In our definition, we propose that hardware developed during the research process would become a research result and is covered under the research hardware definition. Such hardware may range from early prototypes to fully developed and tested research equipment. Over time, such a piece of hardware may be made available to other interested parties, likely including licensing terms. It may be repurposed and/or incorporated as a building block into other (research) hardware. This could be a transitional change where the term “hardware in research” is a better fit than “research hardware”. Such a timeline or transition is likely domain-dependent and hard to pinpoint. We suggest that communities use the different terms at their own discretion.

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