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Leveraging Open Hardware to alleviate the burden of COVID-19 on global health systems

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Summary. With the current rapid spread of COVID-19, global health systems are increasingly overburdened by the sheer number of people that need diagnosis, isolation and treatment. Shortcomings are evident across the board, from staffing, facilities for rapid and reliable testing to availability of hospital beds and key medical-grade equipment. The scale and breadth of the problem calls for an equally substantive response not only from frontline workers such as medical staff and scientists, but from skilled members of the public who have the time, facilities and knowledge to meaningfully contribute to a consolidated global response. Here, we summarize community-driven approaches based on Free and Open Source scientific and medical Hardware (FOSH) currently being developed and deployed to bolster access to personal protective equipment (PPE), patient treatment and diagnostics.

In recent days and weeks, governments around the world have called upon industry to address key shortcomings in the global response to COVID-19 - for example to produce more personal protective equipment (PPE), ventilators and diagnostic tools [1,2]. While this is an important part of any country's response, the capacity of existing industry to meet the scale of the challenge is likely insufficient. Moreover, it is set to first address shortages locally where relevant industry is based, rather than globally, and medical grade equipment and kits emerging from this process will be costly, at a time where the economy is taking a big hit. Accordingly, relying on existing industry alone to supply adequate quantities of much needed tools is likely to be insufficient: innovation and novel manufacturing pipelines are required.

Here, one complementary key access route to much needed tools and equipment is via Free and Open Source (scientific and medical) Hardware (FOSH). FOSH follows the ethos of open source software, where all blueprints for a tool are made freely available so that anyone can study, learn, modify, customize and commercialize them [3,4].

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Studies and practical experience with FOSH has shown key benefits that are paramount for disaster situations: fast and distributed development based on the contributions of many people who are for the most part working remotely [5,6] is advantageous given the social distancing measures in place in many COVID-19 affected countries. The typically much lower implementation costs of FOSH [7] and, importantly, easy adaptability to local resources are key further benefits of an open hardware approach. Finally, and perhaps most importantly, any new hardware designs or improvements thereof are by their very definition globally available. Anyone equipped with the necessary knowhow, tools and time can build on this knowledge to meaningfully support their immediate community. The importance of the latter cannot be overstated: Different communities face different limitations in the availability of trained staff, medical consumables and machines as well as diagnostic tools. Accordingly, what may be limiting in one place may not be limiting in the next, and any global response must therefore be adjusted to local realities. Here, the many benefits of a FOSH approach allow for fast, local deployment, bypassing traditional production chains, and flexibly supplying affected areas as they emerge.

A FOSH approach to supporting global health systems. Increasingly over recent years, scientists, engineers and hobbyists alike have jointly developed and tested an impressive array of open source and state of the art tools that in one way or another touch essentially all aspects of modern biology, medicine and disaster response (e.g., [8–19]. For example, in the wake of the 2011 Fukushima nuclear disaster, Safecast [6] developed FOSH Geiger counters alongside an open access logging system which led to a massive citizen-science driven map of nuclear contamination in the region [6]. Now the same group is stepping up to meet the challenges of COVID-19, for example in the form of a daily curated newsletter [20]. More generally, existing community driven FOSH designs relevant to the current situation range from simple tools like DIY-facemasks [21,22] or 3D printed valves to regulate airflow in ventilator tubes [23] to state-of-the-art scientific instruments for diagnosis such as an automated pipetting robot [24], plate readers [25] as well as a wide range of medical tools and supplies [18]. Diverse further initiatives, including numerous designs for FOSH ventilators [26–34] are well underway. Here, we provide a brief overview of the current state of the art in available designs and ongoing community projects aiming to leverage FOSH to meaningfully contribute to a global response to the current crisis. In the specific background of COVID-19, we here highlight a subset of available projects centered around:

1. Personal protective equipment (PPE) such as masks and visors

2. Patient treatment, focusing on ventilators

3. Diagnosis tools, focusing on scientific equipment and test-kits

An important note of caution. *When implementing any of the projects mentioned in this article, it is important to critically evaluate the reliability and safety of the design on a case by case basis. While some designs have been extensively tested and verified, others are at best anecdotally verified and are intended for research use only. While this is important in all aspects of FOSH, it becomes imperative when considering diagnostic and medical tools. Use of these designs in a clinical setting may be prohibited by local regulations.*

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1. Building your own personal protective equipment (PPE)

Buying a facemask off the shelf is becoming increasingly difficult, and people are understandably looking into do-it-yourself (DIY) options that may serve as a useful replacement. Similarly, hospitals are running out of specialized personal protective equipment (PPE) for medical staff, which typically includes both a mask and a visor, alongside specialized clothing and gloves. Here, we will focus on DIY masks and visors (Fig. 1).

First, it is important to consider what level of protection is required. For example, masks come in many varieties, with different purposes and regulatory standards. Some simpler masks (often called surgical masks) are intended to be used by the infected person to reduce spread of infection by catching large droplets, for example after coughing and sneezing. Such masks are fairly easily home-fashioned (e.g. Fig. 1A), and can to some extent be considered a useful tool to reduce spread of infection from already infected persons [35]. However they are not usually thought of as an effective form of protection from becoming infected in the first place [21,22,35]. For a summary on the role and use of various types of masks, the reader is referred to official World Health Organization (WHO) advice [36].

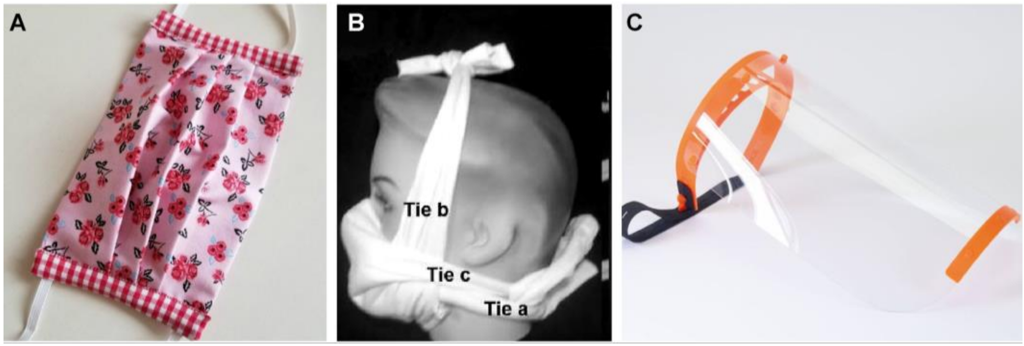

***Figure 1 | Examples of DIY masks and a visor**. **A**, One of many designs for a home-made cloth-mask [37], **B**, Somewhat more effective cotton T-shirt based mask [21], **C**, 3D printed and laser cut face shield [38].*

In contrast to surgical masks, so called N95 filtering facepiece respirators (FFRs) are intended to provide some level of protection to the wearer, and they are for example used by medical staff tending to infected patients. Unlike surgical masks, these are designed to seal against air slipping through gaps between the skin and the mask, and they contain a specialized filter that acts as a physical barrier to particles down to 0.3 microns. This is still bigger than the actual virus (~0.12 microns) [39], but substantially smaller than most droplets coming off a sneeze or cough. The performance standards for such masks are tightly regulated, and any DIY approach replicating them (e.g. Fig. 1B, [21,40]) must take careful reference to these regulations. For example, it has been argued that the porosity of 3D printed materials make them a risky choice for masks as they may allow viral droplets to persist for prolonged periods of time [38]. Possible gaps in the material itself (e.g. due to blistering or imperfect layering during printing) add further room for concern. Accordingly, controlled testing of existing and upcoming N95-like FFR prototypes is paramount. Moreover, unless worn correctly they may end up being no more useful than a surgical mask [36].

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Right now there are many DIY-recipes for various types of masks out there, from simple video tutorials based on napkins, cloth or bra-cups [41–43] via 3D printed options [40] to designs developed and/or tested in peer-reviewed scientific studies [21,22] (Figure 1A,B). Some are quite effective [21], however to our knowledge none fully comply with regulatory standards of N95 FFRs for medical use. Nonetheless, with designs currently being published on a daily basis, this may soon change.

In comparison, a state-of-the-art DIY visor (or face shield) is arguably easier to build, in part because it does not need to seal tightly against the skin. An online search quickly reveals several designs [44,45], including one notable initiative from Prusa, a leading open hardware manufacturer for 3D printers. They are currently using their sizable 3D-printer farm to supply 1,000s of Open Source visors (currently designs are provided under a non-commercial license in an attempt to avoid commercial exploitation [45]) to the health ministry in the Czech republic (Fig. 1C, [38]). An alternative approach coming out of Stanford is based on existing full-face snorkel masks [46] which would effectively serve as a combined mask and visor. Efforts such as these, including their important experimental verification (see above), could easily be scaled with minimal investment and may be more easily disinfected for reuse compared to masks [38,47].

2. FOSH Ventilators

Ventilators are medical devices used to deliver gases (ambient air or oxygen enriched mixtures) to patients for breathing-support. They can be as simple as manually operated compressible bags, or fully computerized machines that regulate gas pressure, humidity, their relative concentrations as well as cycle rate, while taking real time measurements to monitor patient condition. The interface between a ventilator and the patient can be implemented invasively (intubation) or non-invasively (via a mask or a cannula system on the nose). The added complexity of some more modern systems makes them more suitable for prolonged use, as they better mimic physiological conditions and can be adjusted to specific patient needs. The United States National Institutes of Health (NIH) provides a general overview on ventilators and their use [48] including a wide range of interface types, ventilator functions and other details that are not covered in this article. A detailed account of ventilators in a clinical setting can also be found at [40], and the UK recently published their own specifications for ventilators to be used in hospitals [49].

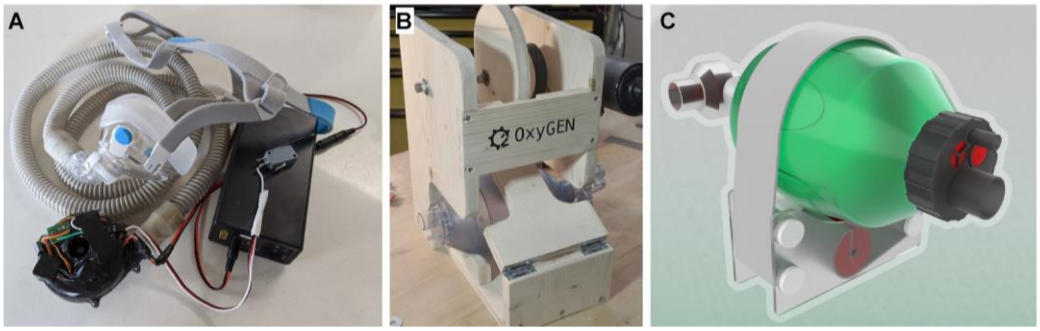

***Figure 2 | Examples of FOSH ventilators**. **A**, Arduino based ventilator* [27], ***B**, OxyGEN ventilator bag automation system* [33], ***C**, Prototype rendering from Open Source Ventilator initiative* [50].

The use of non-invasive systems for patients with COVID-19 in hospitals is currently debated due to their potential to create aerosols which increase the risk of infecting others [51]. Nonetheless some have argued they may have a place under certain circumstances [52], and it is moreover possible that such systems may come into increased use as the situation worsens. However, where available, invasive systems generally remain a preferred option.

Already now, and likely more so in the near future, availability of ventilators for patient care is limiting [53–55]. Current efforts to address this impasse include the stopping of elective surgeries to free up existing systems [56], the recommissioning of disused models from storage, and a plea to industry to ramp up production [1,57]. In parallel, diverse groups around the world are rallying their communities to design FOSH-solutions that will help increase the availability of ventilators (Fig. 2) [26,27,29,30,33,34,50,58–62]. Some examples include the development of complete and stand-alone systems [59,63] (Fig. 2A), the automation of manual ventilators (Fig. 2B,C) [27,29,33] and the repair of existing but out of use equipment, e.g. with 3D printed replacement parts [62,64]. Many of these projects are actively looking for collaborators with various backgrounds.

3. FOSH approaches in COVID-19 diagnostics

The WHO recommends that countries should prioritize case finding, testing and isolation as a main strategy to slow down the spread of the virus [65]. This means that testing must be made widely available. The diagnosis of SARS-CoV-2 involves sample collection, usually from nasopharyngeal or oropharyngeal swabs [65], followed by RNA extraction (SARS-CoV-2 is an RNA virus), specific amplification of the RNA and finally detection. The most common diagnostic procedure involves the use of a commercial kit for RNA extraction, followed by quantitative Reverse Transcription Polymerase Chain Reaction (qRT-PCR) [66] which requires several types of hardware, chemicals and reagents to be deployed and typically takes place in a regulated lab that meets ISO 15189 standards for diagnostics [67].

Item	**Selected examples of current CDC/FDA-approved items**	**Status of Open Source alternatives** *Note: these protocols and devices are not yet approved for diagnostic use in any jurisdiction at the time of writing.*
RNA Extraction Kit	Qiagen QIAamp® Viral RNA Mini Kit Roche MagnaPURE Total Nucleic Acid Kit	There are numerous published protocols to extract viral RNA from swabs using standard laboratory reagents, for example: ● Trizol and ethanol technique [68] ● Magnetic Bead-based extraction [69] ● Direct RT-PCR from crude samples [70]
qRT-PCR Mix	Thermo Fisher Scientific® TaqPath 1-Step RT-qPCR Master Mix	Consists of multiple components: **Enzymes** (e.g. MMLV reverse transcriptase and DNA polymerase) can be produced in most labs from DNA vectors. Early versions are already off-patent and sequences are available from the Open Enzyme Collection [71] and Free Genes [72]. Later versions are patent-protected in some jurisdictions but not all. **dNTPs** require specific manufacturing capabilities and are currently readily available commercially in bulk. **Buffers** typically use standard lab chemicals and are often published but may be proprietary.

Primers	CDC Primer Set and others approved under FDA Emergency Use Authorization [73]	Several primer designs have been published as open data and can be synthesised commercially by any company but for diagnostic use the company and reagent batches should be validated and approved by the relevant local regulatory body.
Positive Control RNA/DNA	Positive controls are distributed with CDC kits by the International Reagent Resource [74]. Genomic RNA positive control available through BEI Resources [75].	SARS-COV-2 genome and control sequences are open data and can be synthesised commercially by any company but must be approved for diagnostic use. Control reagents are available from [76] in the US and from relevant agencies or the WHO elsewhere.
Automated RNA Extraction Platform	Qiagen EZ1 Advanced XL Roche MagNA Pure LC bioMérieux NucliSENS® easyMAG® Instrument	OpenTrons [24] is an open source automated platform that can work with a variety of generic reagents.
qPCR Thermocycler	Applied Biosystems 7500 Fast Dx Real-Time PCR System with SDS version 1.4 software	Open qPCR [77] is partially open hardware. There are currently no fully open alternatives.
Centrifuges	Refrigerated high-speed centrifuge	No open designs yet with suitable specifications. Existing centrifuge designs [78–80] are usually designed for low-speed separation of plasma at ambient temperature. Centrifuges and compatible consumables are widely available from generic manufacturers.
Heat block/Water bath	Heat block/Water bath with 30-90°C temperature range	No open heat block designs yet, water baths have been described using microcontrollers and immersion heaters but the simplest available solution is use of a sous vide cooking device [81]. Heat blocks and water baths are widely available from generic manufacturers.
Pipettes	Adjustable micropipettes that meet ISO 8655 Standard in the range 0.5 µl to 1000 µl	Adjustable micropipette that meets ISO 8655 Standard down to 30 µl [82]. Note that this volume is not low enough for use in typical *in vitro* diagnostic testing. Adjustable micropipettes and compatible consumables are widely available from generic manufacturers.

***Table 1 | Diagnostic hardware and reagents with open source alternatives**. We have selected FDA/CDC-approved items as an illustration but each country will have its own regulators and agencies with different sets of approved equipment and reagents. Many countries are choosing to simplify or accelerate regulatory approval during the COVID-19 pandemic.*

Central testing labs overwhelmingly use automated sample extraction systems and other hardware that have been validated by the FDA and CDC in the US or the national equivalent in their local jurisdiction. These are supplied by a small number of large companies (e.g. Qiagen, Roche and Abbott) with vertically integrated business models: only proprietary reagent cartridges and plastic pipette tips for processing samples will fit the instruments and there are no or few generic suppliers. This is one of the reasons for acute shortages that have led to calls for donations of reagents and instruments from academic labs to bolster public health efforts.

There has also been unprecedented rapid and open sharing of diagnostics and devices through preprint publications, and through informal communication routes among researchers [68,83–85]. For example, agencies in China, Germany, Hong Kong, Japan, Thailand, South Africa and the United States have shared protocols for molecular assays online including the DNA sequences to detect the virus. Others are now reproducing these in their own labs as well as commercially [66,86]. Meanwhile, large

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sums of money are being invested in universities, public hospitals and the private sector to develop rapid point of care (POC) or near-POC devices to enable scaling of testing in clinics, temporary facilities and even homes.

All reagents and devices used for diagnostics are typically regulated in terms of their manufacture and use meaning that "home-brew" or DIY solutions are typically not acceptable unless the lab developing and using them is itself certified and then only under certain conditions. In some jurisdictions regulations are becoming simpler or accelerated during the COVID-19 emergency and novel tests are starting to get approval for diagnostic use through the FDA's Emergency Use Authorization (EUA) scheme [68], WHO's Emergency Use Listing and other national schemes [87]. The transparent and international sharing of protocols at inter-agency level is capable of driving forward testing while academic and commercial projects catch up and apply for emergency approval status.

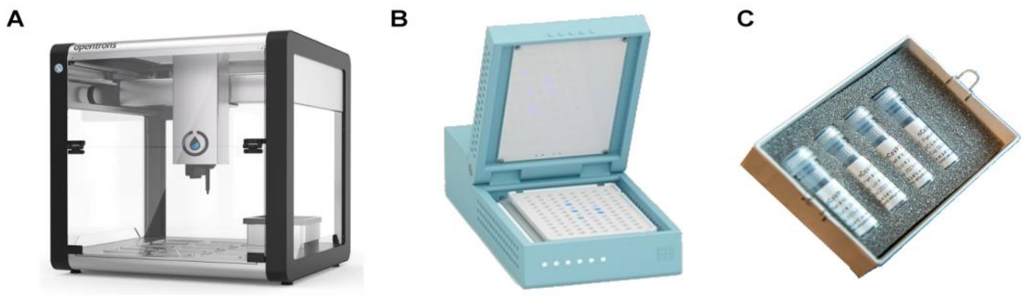

Figure 3* | *Examples of FOSH designs with potential use in diagnostics*.** ***A*, OpenTrons* [24]*, a liquid handling robot* ***B****,* Miriam, an incubator and reader for isothermal amplifications e.g. LAMP [88]*.* ***C****, US CDC Primer and Probe Kit for diagnostic tests* [89].

Community and commercial open source efforts in diagnostic technology to date have focused on four areas: i) open platforms for scaling reactions as exemplified by Opentrons (Fig. 3A) [24], an open source lab automation platform that is working with BP Genomics and the Open Medicine Institute to automate up to 2,400 tests per day and achieve US FDA EUA approval; ii) trying to fill gaps where less attention is being paid by clinical diagnostics companies, such as Chia Bio's Open qPCR (Fig. 3B) environmental test kit for surveillance via surface swabs that is applying for the Open Source Hardware Association Certification scheme [90]; iii) distributed reproduction of rapidly-published, lab-scale protocols, seen within the OpenCOVID initiative hosted by Just One Giant Lab [91] which involves many community labs worldwide; iv) initiatives such as the Open Enzyme Collection [71], Free Genes [72] and Biomaker Challenge [92] which are investigating new approaches to foundational technologies such as reagents and instrumentation, with a view to building capacity and resources or global science and medicine to face a future pandemic.

These efforts supplement a wide range of existing open hardware and off-patent, generic biotechnologies which could play a role in expanding molecular testing capabilities [4,93–96].

In addition, the development of alternative diagnostic techniques could help bypass some of the hardware requirements. For example, recently published protocols based on Cas enzymes [83,84,97], ligation-dependent detection [98] and colorimetric RT-

LAMP [99,100] obviate the need for a qPCR machine. In particular, DETECTR combines RT-LAMP [84] with Cas12a, requiring only pipettes and two heat blocks or water baths in terms of instrumentation. The readout can be done via inexpensive lateral flow strips, through a plate reader, for which open hardware alternatives exist [25], or if need be even by eye. Although most of these enzymes and protocols are patent locked, they would be available for manufacturing and use in areas where patents were not filed, which likely includes many countries in the global South. The implementation of these technologies in countries with very limited testing resources could be a game changer in the global control of the Covid-19 pandemic, particularly when combined with protocols for RNA extraction that do not depend on commercial kits ([68–70], and Table 1). For this reason, development of rapid diagnostics for use at the community level was #1 in the WHO's eight immediate research actions agreed as part of their 2019 Novel Coronavirus Global Research and Innovation Forum [101].

The scientific community is coming together to find and implement faster and cheaper diagnostics, which could be instrumental to control the pandemic, particularly in the medium term amid fears of the so-called "second peak" if and when the strict isolation measures put in place in many countries relax. The diagnostic supply chain issues we face currently highlight the risks of under-investment in public diagnostic infrastructure and of vendor lock-in, resulting in reliance on a small number of suppliers. Efforts from the open hardware community to design and produce rate-limiting equipment and reagents (see Table 1) could offer a long-term mitigation strategy, allowing rapid scale up of manufacturing of generic designs and recipes, given sufficient political will and investment.

Conclusion and outlook

In the above, we have summarised a subset of current FOSH related initiatives aiming to meet the global challenge of COVID-19. However, our account is by no means comprehensive, and the situation changes daily. Accordingly it remains important to continuously seek up to date information, for example by following live documents curated by the community on various aspects of the FOSH response [29,33,61], and to join key community portals and mailing lists [19,20,61,102,103].

For brevity, we omitted discussions of related approaches, for example the introduction and modification of existing tools from veterinary care [104]. We also did not discuss the important role open-source software and data-collection initiatives can play in understanding and responding to the ongoing and projected situation [105–107].

Most of the technology discussed above is classed as a Medical Device when used in a diagnostic or clinical setting; a challenge faced by only a small number of existing open hardware devices and therefore in need of further research. Moving technology to implementation is perhaps the greatest challenge facing these projects, involving consideration of integration into health care systems, supply chain logistics, regulations and political will. The urgency of the current situation has led to a relaxation of regulatory processes by the US Food and Drug Administration [108] and the European Union [109], with some open source projects already reaching formal testing stages e.g. the VentRap ventilator from the Open AIRE forum is ready for evaluation by the Department of Health of the Principality of Asturias [110].

In conclusion, FOSH approaches are set to play an important part in the global response to our current situation. To what extent they are able to scale a practical response that directly addresses the current wave of need for medical and diagnostic hardware remains to be seen but that is not their only valuable contribution: they are unlocking large and distributed pools of talent, building knowledge, developing innovative designs and fostering capacity and capabilities to tackle this crisis and future emergencies. Like open source software, FOSH works through the eyes and brains of many. The more people join ongoing projects or launch their own and freely share their progress online, the faster and more effective our united global community will be. The time to join is now.

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