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Live Software For RepRap Assembly Workshops

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Abstract

Contents

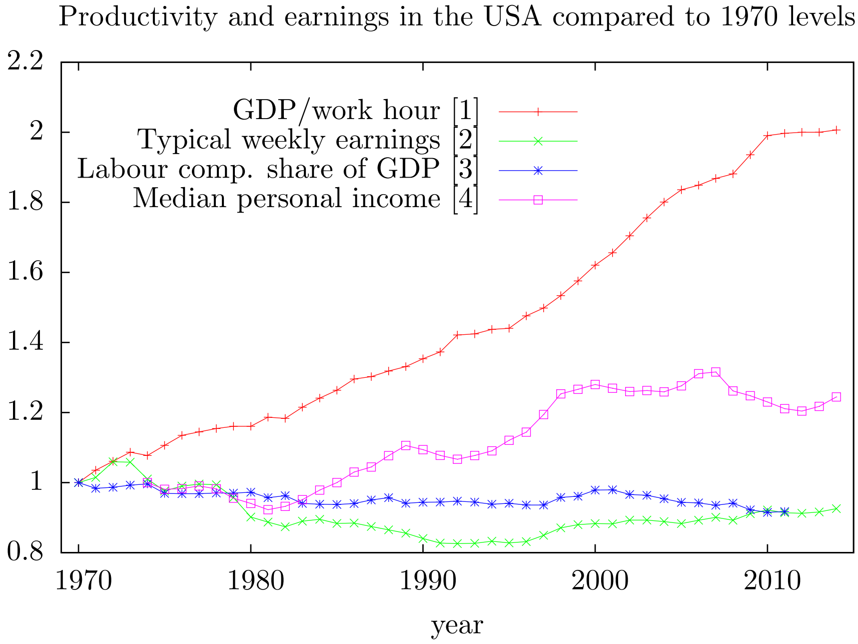

Figure 1: This plot shows that labour productivity, defined as GDP per work hour, more than doubled in the USA between 2014 and 1970. It also shows that typical real incomes have only increased ca 8.5 ± 16 % in the same period. Labour compensation's share of the total GDP is shrinking."Typical earning" refers to that of production and non-supervisory workers in private nonagricultural industries. Prices are constant in relevant data sets. Sources: [1], [2], [3] and [4].

1 Introduction

American organizations have learned to use new production machines like computers and computer controlled robots, and reorganized themselves around them to realize a doubling in labour productivity, as defined above, since 1970.[5, 6, 7, 8]. American individuals have not done the same to their personal incomes[9]. Data on these trends are plotted in Figure 1.

Previous research on distribution of productivity payoff has focused on terms from macroeconomic models, ie alternative real wage measures[10], inflation[9, 11], tax systems[12] and globalization[13]. Proposals on how to boost median wages have been formulated using the same terms.

This paper works towards providing productivity payoffs to median Americans by instead helping individuals and small groups control computers and robots directly. This viewpoint offers routes for engineering contributions to incomes of median Americans, as research have shown that they are generally frustrated and confused by, rather than in control of, computers[14, 15, 16]. We can help to them learn and to stay in control by designing simple and small scale robots and computer programs.

1.1 Copyability and Structural Virality

Being simple and small scale might also ease user copying and distribution of the robots, widening their reach. Under the slogan "wealth without money"[17] the RepRap Project proved the feasibility of user distribution by demonstrating and publishing the design of a 3D printer that was practical for many and legal for anyone to make copies of[18, 19].

In this thesis we refer to the practical ease and legal possibility of making physical copies from a machine design as the design's *copyability*. It describes the ease at which users can become independent suppliers.[1]

A high copyability gives a machine design two important characteristics. First, every part of the copying process that requires human intervention gives that human a level of control. Second, it enables the machines to spread with a high *structural virality*, meaning a high mean path length in a tree structure that describes person-to-person transfers[21]. An economical distribution pattern enabled by a structurally viral spread of production machinery is contrasted with completely centralized production in Figure 2.

1.2 RepRap

RepRap 3D printers were invented during 2005 – 2008[18, 19]. Structural virality of development was high enough that the originators no longer were in control of development by October 2010[19].

The copyability of RepRap 3D printers comes from their free licencing, low price, widely available parts and design files, helpful Internet community and the ability to manufacture a large fraction of their own parts[18]. They have been shown to give a 200 % return on investment within a year for a typical owner[22], although usage and market studies points at major barriers to wider adoption of desktop 3D printers in general[23, 24]. Usage and maintenance complexity have kept adoption to hobbyists with special skills and interests.

[1] A measurement of copyability would require quantitative study of "practical ease" in a wide range of situations, which is outside of the scope of this paper. We know, however, several rigorous concepts that describe aspects of copyability. Some of those who affect the machines in this study directly are *software freedom*, defined in [20], and *self-manufacture*, defined in [18], as well as price, unique part count and availability of documentation.

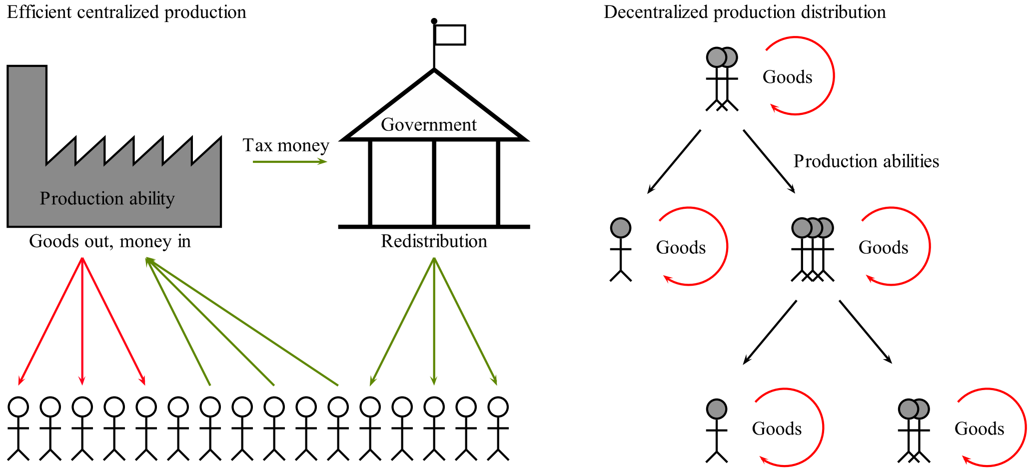

Figure 2: Stick figure explanations of two different models of production and distribution. The left one shows distribution of centrally produced goods coupled with a redistribution cycle of money. In the right model, groups of small scale producers are the main actors and production abilities are distributed, flowing along the black arrows. If every producer would enable new producers at a constant rate, then the right model would result in exponential growth in the number of producers.

The number of RepRaps worldwide is probably well below 1M as of May 2016 (see Appendix C).

The RepRap Project was aware of and actively promoting copyability and the possible structural virality, as made clear in the following comment by Adrian Bowyer, the project's originator:

> "I don't really think that maintaining the position [in the do-it-youself 3D printer- and maker community] is a problem. After all, if every non-replicating 3D printer makes just one RepRap at some point in its life, you can see what that does to population dynamics."[25]

1.2.1 Structural Virality of RepRap Spread

We should however not be tempted to believe that people actually forward copies of everything that is copyable. It has been shown that things as copyable as simple Twitter messages generally spread with relatively low structural virality[21]. To realize the learning and level of control offered by copyability, people need to be motivated to start copying.

The RepRap community is relatively young, and research on what motivates the long term participation and learning required for spreading the machines is sparse. However, all RepRap software is free, libre and open source (FLOS) software, so we expect an overlap between motivational factors of FLOS software communities and the RepRap community.

Motivating factors within FLOS software communities have been found to be diverse[26, 27, 28]. A good review is given in [29], who focuses on understanding sustained participation in FLOS software projects. It finds that social feelings and experiences within the community, especially active contribution, learning and raising expert status, predicts long-term participation far better than factors of initial motivation. We therefore make a distinction between long-term motivation and initial motivation.

Another study found that the level of collaboration among RepRap community members was higher for hardware than for software[30]. We therefore adopt the view that many RepRap community members want to focus on and contribute with hardware modifications, and not software modifications. We assume that social feelings and experiences is as important to RepRap developers as they are to FLOS software developers, but that software skill requirements risk demotivating them from long-term participation.

1.3 RepRap Assembly Workshops

An example of social RepRap community events focused on hardware are RepRap assembly workshops (RAWs). Participants meet up in person to get guided through series of assembly steps, and get the RepRaps they assemble with them home. To show how RAWs have contributed to RepRap spread we shortly describe Josef Prusa's work.

In 2010 – 2013 he hosted a series of RepRap assembly workshops across Europe, funded by pre-selling 3D printed RepRap parts to participants[31]. He instructed 2-day workshops, which was unusually short at the time, using the new and simple Mendel Prusa design[31]. The investigation in appendix C shows that Prusa RepRaps are more numerous than other desktop 3D printers in 2016, counting well over 85 000 copies. Another short investigation (see appendix B) shows that Prusa designs are by far the most popular ones among RAW hosts, but few have used them in 1-day RAWs.

1.3.1 RepRap Assembly Workshop Software Procedures

The investigation presented in Appendix B also shows used software, with the most frequently observed toolchain being the programs

- Marlin[32]
- Arduino Integrated development environment (IDE)[33]
- Slic3r[34]
- Pronterface[2][35]
- OpenSCAD [36]

Marlin is a RepRap firmware, running on a microcontroller, handling sensors and motors. Arduino IDE runs on a PC or laptop and is used to install Marlin onto the RepRap's microcontroller. Slic3r translates 3D models into commands that Marlin understands. Pronterface sends commands (possibly generated by Slic3r) from a PC or laptop to Marlin. OpenSCAD is a program for making 3D models.

Some workshop hosts provided web archives to ease downloading (for example [37] and [38]) for participants. Others offered pre-configured computers for loan during workshop. The Michigan Tech Open Sustainability Technology (MOST) lab used Franklin Firmware and Server instead of Marlin, Arduino IDE and Pronterface, even though Franklin Server does not work on

[2]Pronterface is the Graphical user interface (GUI) of a software suite called Printrun.

Windows[39]. Some hosts provided configuration files for Marlin and Slic3r but no further support, and others didn't offer software support at all[40].

We assume that required software knowledge limits the copyability of RAWs. This is confirmed by a study on RepRap assembly workshops in American high schools. It lists software issues, both troubleshooting and installing, as great barriers to fully realize RepRap's potential in the classroom[24]. It describes the RepRap software tool chain as immature, long and complex, and 12 % of asked teachers rates "3D printer inoperable due to software issue" as an obstacle to integrating 3D printers into academic lessons.

1.4 Live Operating Systems

A possible way to both shorten workshop duration and lower required software knowledge could be by customizing live Operating Systems (OSes) that include pre-configured versions of all the required programs. Live OSes are made to be loaded into portable data storage media such as optical discs or flash drives. Most common laptops can then boot live OSes if configured correctly.

Once booted, users can easily copy live OSes onto more pieces of portable storage.[3] A configured live OS may therefore trade away various software download-, configuration and installation procedures, at the cost of physical storage media, a live OS copy procedure and a boot configuration step per laptop that will be used with the RepRap.

For an overview of how custom live systems can serve specialized communities' needs, see [41]. Previous examples of live OSes configured to portably run a narrow category of applications to serve communities such as makers, bioinformatics researchers, scientific computing researchers and mathematicians include Meikian[42], MASSyPup [43], Knoppix/Math [44], ClusterKnoppix[45], Bio-Linux[41] and TAILS[46].

Five technical factors make live OSes and their portability increasingly functional in 2016.

1. Most laptops now support the same 64-bit processor architecture.

2. Lower price and less technical constraints have made more Random-access memory (RAM) available to laptop OSes, with 4 GiB or more being fairly standard. This allows small but complete OSes to fit comfortably in RAM.

3. Uniprocessor performance growth has slowed down[47, p. 3] which have led to a slower growth in processor requirements of common software.

[3]If their licences permit this. GNU/Linux based ones carry FLOS licences that explicitly permit such copying.

This means both laptops and OSes stay relevant and compatible for longer.[4]

4. Flash storage lifetimes have increased greatly[50, 51] to a level that is usable for live OSes in frequent use.

5. Universal Serial Bus (USB), the bus that portable flash storage is commonly connected to, has gotten faster standards over the past few years. This shortens load times from flash drives to RAM.

1.5 Research Question

We have described increasing labour productivity, its limited effect on real median wages, copyability of RepRaps 3D printers, their potential economic benefits, RepRap assembly workshops, the potential of making them copyable by shortening them and minimizing required software knowledge and the possible solution of configuring live OSes. We have thus motivated the following research question:

> Can RAWs aimed at the general public be shortened to one day without decreasing their copyabiliy by swapping the steps of downloading, installing and configuring software with booting a live OS with pre-packaged software?

[4] A laptop capable of running Windows 7, released in 2009, should be able to run Windows 10, released in 2015, according to Microsoft[48, 49].

2 Method

2.1 Overview

The research question was tested through trial-and-error in a full experiment. A live OS was configured in Sweden and sent to Open Source Ecology (OSE), a small organization in Missouri, USA, who tested it in a one-day (12 h) RAW using a Prusa i3 design. After the workshop, participants were asked to fill out a web survey.

We separately tested booting the live OS from a USB drive on a range of different laptop models in Sweden, noting down if they would cause us trouble in a workshop situation.

2.2 Subjects

The main subjects of the study were 2 workshop instructors from OSE, the live OS and 24 workshop participants organized in 12 pairs.

Minor subjects of the study were 12 laptops of different models and 12 Folgertech 2020 Prusa i3 kits.

2.2.1 Open Source Ecology

OSE's role was to test the live OS's fitness for workshop usage. They had previous experience with hosting assembly workshops for tractors and other large machines, and also some experience with using desktop 3D printers from before. They had little experience with software development and GNU/Linux administration. OSE's Internet connection was slow and unreliable during development.

OSE's motivation was twofold. As an organization they depended on workshop revenue to support further activity. They were also motivated by a will to bootstrap viral machine spread. The organization's mission statement revolves around creating an open source economy through distributing production[52].

The workshop was the first in a planned series of RAWs intended to make participants capable of hosting their own RAWs. OSE call this type of enterprise a *distributive enterprise*[53, 54] and the workshop was part of a larger project called *Distributive 3D Printing Enterprise*, often shortened to D3D. More on D3D and distributive enterprises are found in [55, 56].

Table 1: Parameters chosen at [57] when building D3D-Porteus.

Name	Value
Architecture	64-bit
Type	EFI
Boot Mode	GUI
Desktop	Xfce
Timezone	US/Central
UTC Support	Yes
Keyboard Layout	English (US)
Sound Volume	75 %
Web Browser	Firefox
Word Processor	None
VoIP Client	None
Development Tools	Yes
Video Card Driver	Open Source Drivers
Printing Support	None

2.2.2 D3D-Porteus Live Operating System

Keeping size down was a major priority throughout choice and customization of live system because of OSE's slow internet connection and because we wanted to load the entire system into RAM.

Porteus was chosen among many good GNU/Linux live distributions because it was minimal, could be entirely copied RAM, was actively maintained and easy to remaster. It also included an install script that loaded Porteus onto a USB drive without overwriting previous contents.

Other live distributions share these qualities but the Porteus web page also offered a GUI to easily start a custom system build[57]. This gave Porteus a head-start at meeting our customization needs. The simple module system was also considered helpful for customization. Its basic concepts are briefly described in Appendix D.2.

The customized Porteus system was dubbed D3D-Porteus referring to its place in the D3D project.

The web interface gave us a 250 MiB ISO image of Porteus v3.1 as a starting point. The parameters chosen in the Porteus system builder are listed in table 1 and some of them are briefly commented in Appendix D.1.

A special boot mode called "D3D Workshop Mode" was configured. It enabled copying the entire live OS to RAM and executing Pronterface automatically upon boot. It specified no automatic storage of system changes. That is, any changes to files or folders while in D3D Workshop Mode were discarded upon reboot. See [58] for all boot flags used and [59] for explanations.

Installation instructions were compiled and published at [60] to help hosts create live USB drives with D3D-Porteus.

The D3D-Porteus files are hosted at [61].

2.2.3 Programs

We chose to package and include the programs listed in Section 1.3.1 into D3D-Porteus. Arduino IDE, OpenSCAD and parts of Printrun (Pronterface) were compiled from source. Technical aspects of the compilation process is outside of the scope of this paper but the packaging process is briefly described in Appendix D.2.

All the D3D-Porteus specific configurations of these programs were put in a separate module called `D3D_Workshop_Configuration_64-bit_4.xzm`. These configurations were aimed to save in on the number of clicks required to upload firmware and start a test print. With the configuration in place each of these tasks took 5-7 clicks each.

No code outside of configuration files was changed.

2.2.4 Hardware

The workshop had 12 unassembled Folgertech 2020 Prusa i3 kits and 12 USB3 drives loaded with 64-bit D3D-Porteus.

2.2.5 Participants

The workshop had 24 participants. They were of mixed age and skill level. Marketing prior to the workshop was done through Facebook, OSE's home page and local newspapers. It targeted people with an interest in hosting workshops but no particular skill level or age.

The mean payment per participant was $304 and mean payment per machine was $608. Details on workshop economics are provided in Appendix F.

Most participants brought their own laptops, a few borrowed laptops from OSE.

2.3 Measures

A qualitative thematic analysis of web survey and interview responses was conducted. The focused themes was time shortage, long term participation prediction, copyability and experiences with D3D-Porteus.

The number of successfully booted live USBs drives were counted during workshop.

Lastly, our own boot tests were summarized and compared with the workshop boot count.

2.3.1 The Web Survey

The web survey that users were asked to fill out after the workshop can be found at [62]. A copy is included in Appendix E.

Most questions were open ended and allowed long answers. It addressed the RAW as a whole, and the main focus was measuring social aspects and satisfaction. Different aspects of copyability were also highlighted.

Questions 4 – 7, 12 – 14 and 26 focused on overall satisfaction to help understand if the one-day RAW arrangement was appreciated.

Questions 11 and 15 – 17 focused on social aspects to try to predict if the RAW arrangement could initiate long-term participation.

Questions 18 – 20 tried to probe copyability of the 3D printer and tool chain by asking about general level of self-confidence and insecurity associated with the assembly and toolchain.

Question 20 was the only one that mentioned software explicitly. It asked participants if the mechanics-, electronics or software- parts of their RepRap toolchains were most likely to break in ways that they couldn't debug or repair.

Questions 8 – 10 and 21 – 25 tried to probe copyability of the workshop as a whole by asking questions about tools, support and economic feasibility.

Self-rated participant enthusiasm/enjoyment was also collected through the web survey.

To better understand details of the usage problems that participants had with D3D-Porteus, instructors were asked technical questions via a series of emails. These emails focused only on software but were not structured like a survey.

2.3.2 Boot Testing

Any laptop that booted into a usable desktop with a functioning screen image, touchpad and keyboard on first try with the 64-bit version of D3D-Porteus were considered unproblematic. Laptops with 32-bit processor architectures were tested with a 32-bit version of D3D-Porteus but were considered problematic even if the 32-bit version worked.

2.4 Procedures

The major procedure was the execution of the RAW and the subsequent web survey and interviews. Minor procedures were the transmission of D3D-Porteus to OSE, copying of D3D-Porteus onto multiple USB drives by OSE and the separate testing of D3D-Porteus.

2.4.1 Transmission of D3D-Porteus to OSE

Transmission of D3D-Porteus packaged in one ISO file via HTTP (simple web link) was the preferred method of transmission. Sharing the ISO file via Dropbox was used as backup transmission solution.

2.4.2 Workshop Execution

The workshop was conducted March 19, 2016 at the Kauffman Foundation Conference Center, Kansas City.

It started with the RepRaps unassembled, almost all screws unscrewed, almost all wires disconnected, some wires not soldered and with no firmware uploaded on the microcontroller. The extruder and the microcontroller board came pre-assembled from the kit supplier.

Participants were instructed to assemble mechanics, electronics and software in that order. Mechanics were subdivided into pedagogical modules and a large fraction of the mechanical assembly had video instructions. The electronics assembly were instructed through a document with text and images. D3D-Porteus was explained orally to all participants at the same time and there were no videos or documents with software instructions.

Booting and using D3D-Porteus was a separate step at the end of the workshop. At 18:00, that is 10 hours into the workshop, 2 hours before the planned end, participants instructors held a common walk-through on how to boot and use D3D-Porteus. Usage instructions covered how to compile and upload Marlin through Arduino IDE, start Pronterface, connect to the printer, slice a simple 3D model, and start printing it.

2.4.3 The Web Survey

OSE sent an email to all addresses on the participant list, asking participants to fill out the survey. The request to fill out the survey was not repeated.

2.4.4 Boot Testing

Laptops were tested using the following procedure:

1. Boot the laptop and look if the boot-screen informs about which button to press to enter boot configuration.
2. If it didn't, reboot while pressing Esc, F1, F2, F10, F11 and F12 repeatedly.
3. If the laptop still didn't enter boot configuration, do web search of laptop model name + boot USB.
4. Inside boot configuration look for option called "boot override" or similar.
5. If there exist no boot override enable "legacy mode" and/or "legacy first", disable "secure boot" and put USB first in "boot priority order" or similar.

Laptops that required more research to boot or booted into an unusable state, with severe errors in screen, touchpad or keyboard handling, were considered problematic. How to enter boot configuration and what configurations to make were noted down.

3 Results

3.1 Pre-Workshop Copyability

HTTP transfers of D3D-Porteus ISO from Sweden to Missouri were unsuccessful as long download times resulted in timeouts. Dropbox was successfully applied as backup transfer solution.

After several tries, OSE successfully loaded D3D-Porteus onto an initial USB drive using instructions at [60]. Several tries were needed because OSE's Ubuntu installations did not give users the permissions needed to write on external USB drives with VFAT allocation tables. See [63] for OSE's notes on how they experienced and overcame the permissions problem.

OSE managed to copy D3D-Porteus onto 12 more USB drives from within D3D-Porteus. This was done without issues through graphical interfaces.

3.2 The Workshop

The workshop went over time by two hours and had to relocate at 20:00, when the workshop was planned to end and the conference center closed. Participant enjoyment dropped towards the end of the workshop day, as shown in Figure 3.

Net revenue was $4000, or $1333 per OSE member who had instructed and prepared hosting, giving them net incomes of $29 – $61 per person and hour. Details of economic outcome is presented in Appendix F.

Six out of twelve the live USBs booted successfully on participant laptops. Those who managed to boot D3D-Porteus used it successfully, except one participant who missed the information that firmware upload was required.

Two usability problems increased the number of required clicks dramatically, both when uploading firmware and when test printing. The first problem emerged when a Marlin configuration file needed to be changed on all live USBs. This problem was amplified when Arduino IDE and Pronterface disturbed each others' USB communication. Instructors solved the communications problem by rebooting D3D-Porteus, which reverted the change in the Marlin configuration file.

3.3 Thematic Analysis of Survey Responses

The survey was sent to 16 participant email addresses and recieved 6 answers, which gives a response rate of 0.375.

3.3.1 Time Shortage

Participants were frustrated by time shortage, which is visible in Figure 3.

The following comments were made on time shortage of the workshop.

> "I'm not computer or tech savvy so felt rushed.
> ...
> For me it would have been better to do the workshop over 2 days."

> "The conclusion wasn't smooth - it went overtime and had to change locations"

> **Q: What was your least favorite part of the workshop, and why?**
> "Time! [...]"
> "Relocating when we ran out of time caused an upset."

3.3.2 Long-Term Motivation

The time shortage limited the social interactions between participants

> "...I didn't feel like I could help others most of the time because I didn't want to fall behind the group."

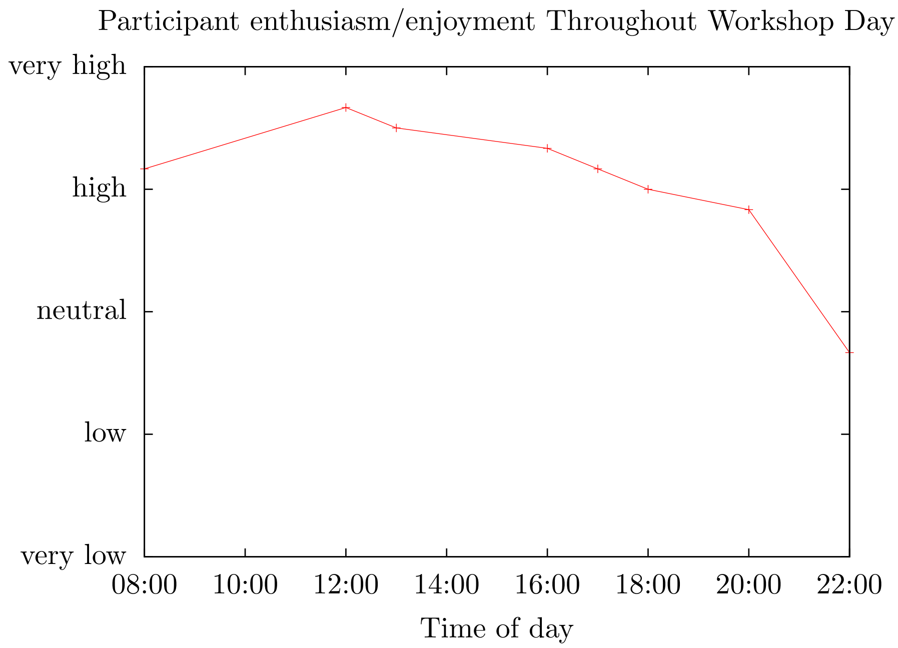

Figure 3: Participants were asked to recall their feeling of “enthusiasm/enjoyment” at various times of the workshop day and rate it along a five-step scale. The workshop was planned to start at 08:00 and end at 20:00 but went overtime by two hours. The plot shows the mean of their answers, assuming a linear scale between the five response alternatives. Lines between data points is not meant to imply perfectly linear development, only to highlight the trend.

> **Q: Were participants able to help each other out? Why/why not, and in what ways?**
> "Yes. Although, at times it seemed people felt rushed and got significantly ahead from others who were slower, instead of helping."

Four mentioned meeting other participants among their favourite parts of the workshop. One mentioned meeting instructors as a favourite part of the workshop.

Those who did not focus on social interactions when describing their favourite parts of the workshop mentioned challenge, pride and satisfaction with building the machines and using them for the first time.

> "I have a 3D printer...! This should enable me to move forward with some personal projects and skill building..."

> **Q: What was your most favorite part of the workshop, and why?**
> "seeing it move for the first time, "I built this""

One out of six participants mentioned prior workshop participants as someone to ask for help with eventual hosting preparations. One mentioned an instructor.

3.3.3 Copyability

Three participants responded that they intend to host a workshop themselves, two responded "Maybe" and one responded "No". No participants mentioned software among what they would consider challenging or needed support with if they were to host a RAW themselves. The challenging subjects that did get mentioned were very diverse.

> "Next phase design [...]"
> "resource channels, parts sourcing etc..."
> "Assistance. Motivation."
> "[...] marketing, networking, and financials [...]"

3.3.4 D3D-Porteus Functionality

Four out of the six respondants regarded software as the single link in their 3D printing toolchain that was most likely to break in ways that they were unable to debug or repair. Two participants mentioned software among the most challenging parts of the assembly. Electronics wiring were considered more challenging than software on average, as it was mentioned three times.

There were frustration associated with getting D3D-Porteus up and running.

> **Q: How would you rate your instructors? Did you feel you got sufficient support? What was missing?**
> "Definitely spread thin on instructor ratio regarding software, computer setup"

Two participants were unable to boot D3D-Porteus on their Macbook laptops.

> "... my older Macbook Pro didn't boot from the USB stick"

> "... getting the D3D live Linux ISO to boot on my borrowed Macbook did not work, it had something to do with the OSX version () and EFI bootloader, so I had to borrow someone else's laptop which slowed both of us down..."

Another participant missed the firmware upload step completely and thus failed connect with Pronterface.

3.4 Instructor Comments

Host and head of OSE, Marcin made the following conclusive comment

> "Software remains to be addressed. Half the people had issues with the live USB, perhaps the 32 bit version could have helped - but not for certain, as nobody had an older computer."[64]

Instructor Catarina summarised complications during D3D-Porteus usage like this:

1. Some people couldn't boot from the usb on their laptop.
2. We couldn't write to the disk.
3. We couldn't have 2 usb ports open at the same time.

3.5 Boot Testing

The laptops we tested outside of the workshop are listed in table 2. A larger list including contributions from the Porteus community and with further links is found at [65].

Table 2: Laptops Configured to Boot D3D-Porteus Prior to Workshop

Laptop Model	Problem?	Button	Comment
Acer M5-581TG	No	F2/F12	F12 enters "boot menu".
Asus g74s	No	Del	Mark USB in "boot override".
Asus Zenbook UX32A	No	F2	Hold F2 while rebooting.
Dell Precision M6500	No	F12	
HP Pavilion zt3000	Yes	F10	Old. Works with 32-bit version.
Lenovo g580	No	F2	... or power with "Novo button"
Lenovo SL300	No	F12	
Lenovo Thinkpad SL510	No	F1	... or "Thinkvantage button".
Macbook Air from 2011	No	Option	Press and hold while powering.
Dell XPS 13 from 2016	Yes	F12	Problem with graphical mode.

4 Discussion

4.1 Result Discussion

The research question was

> Can RAWs aimed at the general public be shortened to one day without decreasing their copyabiliy by swapping the steps of downloading, installing and configuring software with booting a live OS with pre-packaged software?

The answer is no. Percieved copyability of the RAW seems intact since three participants intend to host workshops and don't mention software as an obstacle. However, a boot success rate as low as 50 % risks prolonging RAWs rather than shortening them.

The results document that OSE did host a one-day RAW. It also shows that shortening to one day led to a time shortage that would have been problematic even if the software part of the workshop was cut out completely, as the mechanical assembly and wiring took the first 10 workshop hours.

OSE and RAW participants had initial difficulties with writing to and booting from USB drives. Once booted, D3D-Porteus worked, but not optimally.

4.2 Method Discussion

The difference between the no-problem-rate of table 2 (80 %) and the recorded boot success rates during the actual RAW (50 %) shows the strength of the full experiment trial-and-error approach. The insight that discarded file changes upon reboot surprised users, and that this actually slowed the workshop down could also have gone missed in an isolated experiment.

The downside of doing a full experiment was costs in time and money, which led to relatively few data points. The web survey also had a low response rate. This made many results into mere pointers that requires additional research to confirm.

Even if OSE directed their marketing towards the general public, it is probable that many participants had knowledge and an interest in OSE's activities from before. This might bias the impression of copyability given in the web survey responses. Even though three of six respondants planned to host RAWs themselves, we do not believe that the arranged RAW would turn every second randomly chosen American into a potential RAW host.

We started this report with plotting multiple economical indicators, among them "labour's share of GDP". These indicators were used to describe the economical development of typical Americans. The solution we proposed of increasing copyability of production machinery would maybe not change these indicators directly, even if it spread virally and changed Americans' economy drastically. This is because of how GDP is measured and how labourer is defined as well as how their share is measured. An overview of the limits of GDP is available in [66], and problems related to defining "labour's share" is available in [67].

4.3 Further Work

To make D3D-Porteus useable, it needs to work with Macbook Pro laptops, as two participants in our small sample had exactly this kind of laptop. One solution would be to include the boot manager rEFInd[68] on the USB drive. It is installable by running a single script in any OS X version prior to 10.11. Loading D3D-Porteus onto DVDs and CDs in both 64-bit and 32-bit versions would also help a few participants.

A weakness with the live OS solution is that boot configuration workload is multiplied with the number of different boot procedures. To get away from handling boot configuration, we would need to make D3D-Porteus into a program running inside any OS. That is, we would need to run D3D-Porteus in a viritual machine. A bundle of bioinformatics software called DNALinux[69] uses this approach, running inside viritual machines created by a proprietary program called VMware Workstation Player. A promising FLOS alternative to VMware is the Docker[70] software, who is in beta for Mac and Windows at the time of writing.

Live OSes is a fairly general purpose technology, so harvesting its potential gains requires adjusting the process in which it is used. One obvious potential is including step-by-step manuals, demonstration videos and all sorts of documentation and multimedia that participants need during an assembly workshop, not only for the mechanical assembly but also for the electronics and software parts.

Utilizing this potential would require booting the live system at the beginning of the assembly workshop instead of towards the end. Starting with the software could give participants a distraction-free computing environment and give them the time to get comfortable with the graphical interfaces of the software. A design and test of a live system for such software-first assembly workshop usage would be interesting future work.

Live OSes could also potentially give participants channels to communicate with each other. It could be implemented as simply as a link on the desktop, and build upon any existing platform, such as forums, social networkning sites, wikis and chat programs. Such a system connected to the Internet would enable distributed and remote first-line support. It would be very interesting to test strategies for promoting a positive group dynamics, and remote support using the live OS as a tool.

A third potential gain from live OS usage could be avoiding Internet dependence. This could make workshop locality an easier and cheaper problem for hosts. It would also eliminate the risk of wasting time on Internet connectivity problems. It would be interesting to measure these effects on cost and time usage and find examples of situations where Internet independence would be relevant.

One aspect of D3D-Porteus usage that we did not investigate was how to best treat system changes. Since the whole system lives in RAM, we have to decide what and when to save anything to disk. The current default choice is to never write automatically to disk, which most users will experience as "nothing is saved, system is restored upon reboot". This has the advantage that unintentionally broken systems can be trivially repaired. USB systems also get independent of the underlying file system (FAT requires special saving mechanisms), and their usage get almost identical to non-writeable CD/DVD systems.

4.4 Author's Last Words And Recommendations

D3D-Porteus could offer a simplification of RAW hosting and RepRap usage if developed further. Our preferred route for D3D-Porteus development would be the following. Re-base the system upon a GNU/Linux distribution with pre-compiled Computer-aided drafting (CAD) packages available. Keep developing it as a live OS. Try using Docker to make executable within any OS.

With that said, there has been very little prior research on RAWs, so mechanical assembly and wiring also contain potential areas of contribution. This paper focused on the live OS but would maybe have been more fruitful if workshop plans were considered as a whole.

The practice of instructing mechanical assembly, then wiring, then software is found in all common RepRap assembly manuals. This was also the case for the Folgertech 2020 Prusa i3 build manual from Folgertech, and it impacted how D3D-Porteus was used. A rationale and rigorous terminology for this pedagogical practice and its alternatives would probably have helped us understand our own work better.

A Acronyms

3d Three-dimensional

bios Basic input/output system

cad Computer-aided drafting

cd Compact Disc

d3d Distributive 3D printing enterprise

dvd Digital versatile disc

efi Extensible Firmware Interface

fat File Allocation Table

flos free, libre and open source

gnu GNU's Not Unix (recursive acronym)

gui Graphical user interface

http Hypertext Transfer Protocol

ide Integrated development environment

lzma Lempel–Ziv–Markov chain algorithm

most Michigan Tech Open Sustainability Technology

os Operating System

ose Open Source Ecology

ram Random-access memory

raw RepRap assembly workshop

tails The Amnesic Incognito Live System

uefi Unified Extensible Firmware Interface

usb Universal Serial Bus

B Web Search Investigation of RepRap Assembly Workshop Plans

Data presented in table 3 was collected by web searching for each individual data point. Many data points were found by looking at pictures, videos, download pages, and build instructions from workshops.

Blank fields means no conclusive data was found. Data generally describes workshop plans and not outcomes.

Some hosts had hosted multiple workshops. The majority workshops accepted 2-3 participants per machine and prices were almost always paid per machine, and not per participant.

The *Designer-Instr?* column tells if a designer of the used model were among the instructors. Josef Prusa co-instructed at least three worskhops that used Prusa designs.

Mendel and Prusa designs are popular RAW models. Orca and Prusa are based on Mendel, while i3 Berlin, Bcn3dand Graber are based on Prusa designs.

Host software are programs for sending commands to RepRaps from PCs or laptops. The table shows two innovative host software approaches. The MOST lab have developed their own coherent software suite including a host software interface that can be displayed by web browsers[71]. i3 Berlin is host software-independent by having controller hardware on the printer itself.

Firmware Uploaders are programs who install programs on RepRap microcontrollers. The table shows innovation from the same two RAW hosts. The MOST lab uses Franklin Server (who is also their host software) in place of Arduino IDE. i3 Berlin trades away Arduino IDE installation procedures by using Cura both as a slicer and as a firmware uploader.

Only three 1-day workshops were found. One of them (Pumping Station One) only taught mechanical assembly. The other two used non-Prusa designs and were as expensive as many 2- and 3-day workshops. Longer RAWs typically included introductions to theroretical aspects of 3D printing, and sometimes introductions to 3D modelling software.

The data in table 3 is found in spreadsheet format at [72].

Table 3: RAW Plans Data Collected By Web Search

Host	Model	Duration	Designer-Instr?	Price/machine
Garage-lab	Prusa i3	2 days	Yes	€850
Garage-lab	Orca v0.43	10-16 h, 1 day	Yes	€1090
MOST lab	Athena & MOST delta	4 days	Yes	
Humboldt	Prusa i2	4 days		
Pumping Station One	Prusa	$\geq$ 8 h, 1 day		\$300 – \$400
Ohm Base Hackerspace	Any	11 h		\$0
Medialab Gdansk	Mendel	3 days		
Daan Uttien, Bart Meijer	Beagle, different sizes	1 day	Yes	€460 – €799
Fablab Berlin	Prusa i3	2 days		€800
i3 Berlin	i3 Berlin	2 days, 18 h	Yes	€1345 – €1545
hive76	Mendel	3 days		\$1200
Poti-Poti	Prusa i3 or SmartRap	20 h		€460
Voxel Factory	Prusa i2	2 days		
Fau Fablab, Aachen	Prusa Mendel	3 days	Yes	
RepRapBcn	Prusa Mendel or Bcn3d	3 days	Only Bcn3d	€740 – €990 + VAT
Bcn3d	Bcn3d+ or Bcn3dR	3 or 2 days	Yes	€995 or €685
Media Computing Group Aachen	Prusa Mendel		Yes	€700
Botbuilder.net	Prusa i3	18 h, 2 days		\$999
Hedron Makerspace	MOST delta	24 h, 3 days		\$1000
ProtoSpace Utrecht	Ultimaker Original	2.5 days		€1795
Ballarat Hackerspace	Prusa i3	12 – 16 h, 4 – 5 days		\$900
Hackerspace Ffm	Prusa Mendel	3 days		
Workshop RepRap Recife	Graber Z35		Yes	2500 – 3500 BRL

Table 3: (Continued)

Host	Year	Host Software	Firmware
Garage-lab	2012		
Garage-lab	2013		
MOST lab	2014	Franklin Server (web browser interface)	Franklin Firmware
Humboldt	2013	Pronterface	
Pumping Station One	2011	No software, only mechanical assembly	
Ohm Base Hackerspace	2013		
Medialab Gdansk			
Daan Uttien, Bart Meijer			
Fablab Berlin	2013	Pronterface	
i3 Berlin	2015	Controls on printer	Marlin
hive76	2011		
Poti-Poti	2014		
Voxel Factory	2012		
Fau Fablab, Aachen	2011		
RepRapBcn	2013		
Bcn3d	2016	Repetier Host	Marlin
Media Computing Group Aachen	2011	ReplicatorG/Repsnapper	
Botbuilder.net	2014	Pronterface	Marlin
Hedron Makerspace	2014	Pronterface, Repetier host, Octoprint	Marlin
ProtoSpace Utrecht	2015	Pronterface	
Ballarat Hackerspace	2016		
Hackerspace Ffm	2011	Bolt v0.3	Sprinter
Workshop RepRap Recife	2015	Repetier	

Table 3: (Continued)

Host	Slicer	CAD Program	Firmware Uploader	Source
Garage-lab			Arduino IDE	[73]
Garage-lab				[74]
MOST lab	Slic3r & Cura	OpenSCAD	Franklin Server	[75, 76, 71, 77]
Humboldt			Arduino IDE	[78]
Pumping Station One	No software	No software	No software	[40]
Ohm Base Hackerspace				[79]
Medialab Gdansk				[80]
Daan Uttien, Bart Meijer				[81]
Fablab Berlin				[82, 83]
i3 Berlin	Cura and Kisslicer		Cura	[37, 84]
hive76				[85]
Poti-Poti				[86, 87]
Voxel Factory				[88]
Fau Fablab, Aachen			Arduino IDE	[89]
RepRapBcn	Slic3r	NetFabb	Arduino IDE	[90]
Bcn3d	Slic3r	NetFabb	Arduino IDE	[91, 38]
Media Computing Group Aachen	Custom FiveD/Tonokip		Arduino IDE	[92]
Botbuilder.net	Slic3r			[93]
Hedron Makerspace	Cura	Meshmixer	Arduino IDE	[94]
ProtoSpace Utrecht				[95, 96]
Ballarat Hackerspace				[97]
Hackerspace Ffm	Skeinforge	OpenSCAD	Arduino IDE	[98]
Workshop RepRap Recife				[99]

C Approximating the Number of Prusa Machines in May 2016

A very rough approximation can be made based on only two data sources 3D Hubs and Thingiverse. The strength of these data is that it is self-reported by 3D printer users rather than manufacturers, allowing home-copied machines to be counted.

Many owners of 3D printers register their machines on `3dhubs.com`, who release monthly data on model number and distribution on `3dhubs.com/trends`. The model numbers of May 2016 are presented in table 4. Assuming that they are representative, these numbers suggest that 10 % of all home 3D printers are either Prusa i3, Mendel Prusa or Hephestos Prusa i3.

The popular 3D model sharing web site Thingiverse claims on their website (on 10 May 2016) that they have 867 690 "community members". We can use this number to estimate the number of 3D printers worldwide, including old, broken and unused machines by assuming that most historical 3D printer owners are Thingiverse community members and most of those who don't own a 3D printer have never register an account on Thingiverse. This assumption is obviously not perfect since one can create an account without owning a 3D printer or even own several 3D printers without creating an account. On the other hand, Thingiverse is widely used within the 3D printing community and has been since its launch in 2008.

The error caused by competing 3D model sharing sites is expected to be small. Alexa is a company who ranks web pages based on estimated unique visitors and page views[101]. It ranks `thingiverse.com` as the 2 956'th most popular website on the Internet. The nearest competing 3D printing specific 3D model sharing site is `youmagine.com`, which ranks at 93 568'th place. `alexa.com` were visited on 11 May 2016.

To check the Thingiverse based estimate, we can use numbers from the Wohlers Report 2016[102]. It estimates that ca 580 000 3D printers under $5000 were sold before 1 Jan 2016, with 278 000 of them in 2015 alone and with doubling numbers every year from 2012 to 2015. This trajectory gets us to 780 000 machines around the time this is written (10 May 2016). Wohlers' numbers concern the number of 3D printers *sold*, a process that many home-copied RepRap machines never formally go through.

Thingiverse user count and 3D Hubs statistics suggests ca 87 000 Prusa i3, Hephestos Prusa i3 and Prusa Mendels combined worldwide. It is surprising that the Prusa i2 does not show up in 3D Hub's statistics since its popularity at its peak was comparable to the peaks of Prusa Mendel and the current Prusa i3.

Table 4: 3D printers registered on `3dhubs.com` sorted by model. Source: [100]

Model Name	Count
Prusa i3	2 352
Ultimaker 2	2 065
Replicator 2	1 412
Zortrax M200	845
Replicator 2x	817
RepRap	724
Ultimaker 1	666
Form1+	658
FlashForge Creator Pro	624
Printrbot Simple Metal	491
Makerbot Replicator 5th Gen	441
Da Vinci 1.0	431
Robo 3D printer	384
Mendel Prusa	348
Rostock MAX	339
Prusa i3 Hephestos	335
Makergear M2	308
Other	16 898
Total	30 138

D Porteus

D.1 Basic Configuration

Extensible Firmware Interface (EFI) and its successor Unified Extensible Firmware Interface (UEFI) are interfaces between OSes and computer firmware that affect booting. Most laptops from 2011–2015 support both EFI/UEFI and the older Basic input/output system (BIOS) interface, but many newer laptops are unable to boot OSes without EFI/UEFI support. A Porteus image with EFI support still also supports BIOS, so the EFI option only increases portability.

The desktop environment Xfce gave a simple desktop environment, simple windows, and a simple start menu. It was also the smallest available pre-packaged GUI, ca 10 MiB smaller than the pre-packaged LXQt. Timezone and keyboard layout was set to suit workshop participants in Missouri, USA. Firefox and open source video drivers were chosen because they gave the most free software among the pre-configured alternatives.

D.2 Modules

Porteus' modules allow users to handle files and directories with logical operations. The most common operation is called *activate*.[5] It corresponds to a logical union of the package and the root directory, as shown in Figure 4. The reverse operation, logical difference with root, is called *deactivate*.[6]

Modules usually contain one program each, so `activate` and `deactivate` do some common install operations automatically. These are often called *activation/deactivation hooks* in other GNU/Linux package systems and include updating desktop icons, shared library links and various system caches.

The command `dir2xzm` compresses a directory into a module that can be handeled by `activate` and `deactivate`. It uses the Lempel–Ziv–Markov chain algorithm (LZMA) and the squashfs file system for compression. `dir2xzm` is rather slow because LZMA is slow, but it reaches a high level of compression compared to other popular compression algorithms like the Hauffman algorithm[103]. Both the reverse operation, `xzm2dir` and `activate` are fast because LZMA decompression is fast.

Both `activate` and `deactivate` can be applied through the terminal or by double-clicking modules in the file browser. `dir2xzm` and `xzm2dir` can be applied through the terminal or by right-clicking modules or directories in the file browser. Porteus modules are named with a `.xzm` file extension.

[5] Other GNU/Linux systems call similar operations *install*.

[6] Other GNU/Linux systems call similar operations *uninstall* or *remove*.

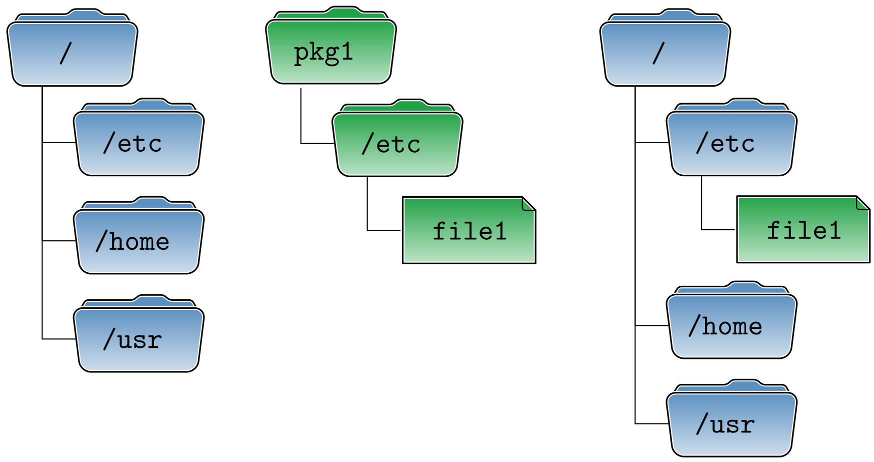

Figure 4: Installing or activating the module `pkg1`. The leftmost tree is a randomly chosen part of Porteus' directory hierarchy. The middle tree (green) is the exact directory hierarchy found in a package called `pkg1`. The rightmost tree shows the effect of activating the package.

E Web Survey

3D Printer Workshop - Followup Survey

Thank you for participating in a 3D Printer 1 Day Build Workshop by Open Source Ecology. This survey is intended to gather learnings on the workshop, so that it can be improved in the future. Further, Torbjorn Ludvigsen - remote collaborator from Umeå University in Sweden - is using this data for his Master's Thesis (http://bit.ly/1U6wbM7) - exploring the 3D Printer as a Distributive Enterprise.

This survey takes 12 minutes to complete. Your name and email is optional if you'd like to keep your answers confidential. Results will be published openly for learning purposes - for other potential workshop organizers. You can view the responses by clicking on the Survey Results link below the survey.

1. **What is your name**
   optional

   ....

2. **What is your email address?**
   optional

   ....

3. **What is your Facebook and LinkedIn page?**
   So we can connect to you.

   ....

4. **What did you like about the workshop?**

   ....

   ....

   ....

   ....

   ....

5. **What did you not like about the workshop?**

6. **What is the most important thing that you learned?**

7. **What are your improvement suggestions?**

8. **Will you be hosting a workshop in the future?**
Mark only one oval.

- Yes
- No
- Maybe

9. **If you will be hosting a workshop, what support do you need to make that happen?**

10. **If you will be hosting a workshop, what do you consider to be the biggest challenge that you will have to address to run a successful workshop?**
Venue? Marketing? Your skill set? Assistace? Part sourcing? Time commitment? Etc.

11. **How would you rate your instructors? Did you feel you got sufficient support? What was missing?**

12. **How did you feel during the workshop day? Rate your overall enthusiasm/enjoyment throughout the day.**
Mark only one oval per row.

	very low	low	neutral	high	very high
8 AM					
12 AM					
1 PM					
4 PM					
5 PM					
6 PM					
8 PM					
10 PM					

13. **What was your most favorite part of the workshop, and why?**

14. **What was your least favorite part of the workshop, and why?**

....

....

....

....

....

15. **Were participants able to help each other out? Why/why not, and in what ways?**

....

....

....

....

....

16. **Will you contact participants or instructors again after the workshop?**

....

....

....

....

....

17. **What adjustment of workshop arrangement would let you connect to participants and instructors more easily?**
    Some people like to talk while building slowly, others prefer assembly efficiently to free up the lunch break. Some love structured introductions, others prefer unorganized coffee breaks. Some like small groups other like big ones etc.

....

....

....

....

....

18. **What was your most challenging part of the assembly, and why?**

....

....

....

....

....

19. **Would you try to fine tune/fix your 3D printer by yourself if needed?**
Mark only one oval.

- ◯ Yes, the workshop gave me that self confidence
- ◯ Yes, but I already had that self confidence prior to the workshop
- ◯ No
- ◯ Don't know
- ◯ Other: ....

20. **What link in your 3D printing tool-chain do you feel are most fragile (most likely to break in ways that you're unable to debug and repair)?**
Mark only one oval.

- ◯ Mechanics: Straightness, flatness, movement smoothness, etc
- ◯ Electronics: Wire connections, replacement part availability, etc
- ◯ Software: Ability to convert 3D models to 3D printer instructions, ability to connect to 3D printer
- ◯ Don't know
- ◯ Other: ....

Tools, support and economic feasibility

21. **If you were to host a D3D workshop, what tools would you need to acquire first?**

....

....

....

....

....

22. **What would you estimate as the cost of tools? Is that prohibitive in terms of cost?**

23. **Do you know who you would ask for help with your preparations?**

24. **How much revenue would you need to make in order to have the interest in organizing a workshop?**

25. **In what other ways than hosting workshops would you consider for generating revenue with your 3D printer?**

26. **Please share any other comments or suggestions.**

F Economics Of Workshop

The workshop generated a net revenue of $4000 that were divided so that three OSE hosts earned $1333 each. Time investment per host is a number that is difficult to approximate because of factors of previous knowledge. A very rough table of time investment per host is given in table 5. Assuming that the approximation is correct within ±12 h for all three hosts, each of them made $29 – $61 per hour.

Economical investments prior to the workshop are listed in table 6. The pricing scheme used is listed in table 7.

Table 5: Approximate time investment per OSE host

Activity	Recurring?	Time consumption
Familiarization with kit	No	12 h
Placing orders	Yes	2 h
Pre-assembly of parts	Yes	4 h
Work hours on workshop day	Yes	10 h
Post Workshop Support	Yes	6 h

Table 6: Economical investments prior to workshop

Item	Recurring?	Total price
3D printer hardware	Yes	$3046
Tools	No	$150
USB drives	Yes	$50
Unused spare parts	No	$20
Room/space	Yes	Donated
Fuel to get there	Yes	$30
Lunch	Yes	Donated

Table 7: Pricing scheme of workshop

Product	Description	Price
Early Registration	Assembly and ownership of 3D printer	$599
Registration		$699
Assistant	Assembly, not ownership of 3D printer	$150
2-for-1 Discount	2 participants, no second 3D printer	$0
Group rate	Negotiated via email	<$699
Remote Participation	Assembly guidance. No 3D printer	$300
True Fans	A 25% discount for OSE sponsors	

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