Not Every Remix is an Innovation: A Network Perspective on the 3D-Printing Community

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ABSTRACT

A better understanding of how information in networks is reused or mixed, has the potential to significantly contribute to the way value is exchanged under a market- or commons-based paradigm. Data as collaborative commons, distributed under creative commons licenses, can generate novel business models and significantly spur the continuing development of the knowledge society. However, looking at data reuse in a large 3d-printing community, we show that the remixing of existing 3d models is substantially influenced by bots, customizers and self-referential designs. Linking these phenomena to a more fine-grained understanding of the process and product dimensions of innovations, we conclude that remixing patterns cannot be taken as direct indicators of innovative behavior on sharing platforms. A further exploration of remixing networks in terms of their topological characteristics is suggested as a way forward. For the empirical underpinning of our arguments, we analyzed 893,383 three-dimensional designs shared by 193,254 members.

CCS CONCEPTS

• **Information systems** → **Collaborative and social computing systems and tools**; • **Applied computing** → *Education*; • **Hardware** → *Emerging tools and methodologies*;

KEYWORDS

networks, 3d printing, online community, innovation, remixing

1 INTRODUCTION

Reusing information is key to the continuing development of the knowledge society and the emergence of the Zero Marginal Cost Society, that is the paradigm shift from market capitalism to the collaborative commons [32]. Rifkin envisioned an era, where competition leads to ever leaner production mechanisms and sharing platforms turn consumers into prosumers as they create, adapt and remix existing designs into personalized designs [32] . Hence, data is not only the new oil but also the basis for a new understanding of how value is exchanged, within a market- or commons-based framework. Data as collaborative commons can thereby make established business models obsolete.

An example of platform collaboration are 3d-printing communities, sharing and remixing their 3d models. Remixing as a form of peer production is also referred to as a shift towards a more collaborative culture, increasing the quality of collaboration outcomes, since members of the 3D printing community can iterate and refine each others' designs [8]. More generally, remixing describes the practice of "taking ideas and modifying or recombining them " [27].

One of the stated goals of Web science is to track and reflect upon large-scale platform activities and explore, for example, the extent and nature of sharing that can be found [20] . Developing a richer understanding of platform activities is not only critical for economic reasons, when knowledge production and use is often shared among thousands of users, but it is also hugely relevant if we search for design principles that might facilitate or limit specific forms of collaboration [9].

The specific sharing platform we analyse in this paper is Thingiverse.com, a platform providing reusable designs at an entry-level, as well as meta-models or complete design files using 3D modelling applications such as OpenSCAD, Blender or Fusion360. Whereas the first two file formats are generated by free software, the latter requires a commercial digital prototyping tool, where free licences are granted, but only for educational purposes. By the end of 2017 Thingiverse featured more than 993,850 3D Models or Things and states on its Website to represent the world's largest 3D printing community [37].

3D printing is a hugely dynamic area, becoming ever more accessible to a growing number of tech-affine tinkerers [41]. 3D printing is also a corner stone of the Maker movement, which lowers the entry barriers to innovation by enabling fast prototyping and experimenting with ideas [39]. While declining in price, printing materials are constantly improving, printers become more reliable and the opportunities seem limitless, as indicated in an early cover story from the Economist in February, 2011, which said "Print me a Stradivarius" [14].

The specific background to our paper is the question whether Thingiverse content can support educators, either by identifying models useful to their specific subject matters (e.g. geometric shapes,

miniature models of cells or a Pythagorean cup, showing the transmission of fluid-pressure) or by providing models students could adapt and print themselves.

2 RELATED WORK: REMIXING 3D-MODELS AND INNOVATION

Innovation, collaboration and knowledge reuse are research topics, that have gained in interest among researchers of maker communities[27–30]. Platform usage data have been used to explore

- the differences between collaboratively and individually authored projects in Scratch, a programming platform for youth [21];
- the accessibility of maker knowledge based on discourse styles [40]or
- the participation patterns of female and male makers, on Instructables.com [35].

2.1 Remixing 3d-models

Thingiverse data, as well, have been analysed previously, e.g. testing whether meta-models - parametric models easily adaptable through slides or web forms - are reused more frequently than other types of 3D models which would require the use of a text editor or a specific CAD program to make the desired adaptations [24]. This hypothesis could be confirmed, moderated by the community experience of the meta-model's designer, i.e. their duration of membership or the number of designs they had already provided to the community. Another stream of research is looking into remixing patterns, i.e. exploring the originality of adapted designs, whether remixes transgress design categories or the structural diversity of remixes (e.g. number of sources or derivatives) [17]. Related to users' remixing behaviour, is the provision of non-physical knowledge, that helps novice users in the process of fabrication, e.g. step-by-step descriptions, indication of parameters for different 3D printers and filaments, successfully used with a specific design [28].

Another, equally relevant, stream of research takes reuse of design knowledge as a means to explore other, higher level concepts such as open innovation and co-creation. For example, co-creation can concern different stages of the making process as in users downloading a 3D model and printing it themselves instead of sending it to an on-line printing service [31]. Whether or not 3D models can be considered open innovations, according to the authors, depends then on whether they are used by a community in response to an actual need [38]. The latter can be supported by commercial or non-profit organisations, but could also be the result of a more informal bottom up movement. Research has shown, that there is also a strong component of craftsmanship behind the process of 3d printing. This takes often the form of tacit knowledge, since it is not hard-coded within the actual 3d model. An important source for clarifications is the built-in discussion platform here, where some design have drawn hundreds of comments. The most common questions included: (a) knowing how to actually use the 3d object correctly, (b) how to customize or remix a design, (c) print quality on a given printer and (d) how a design was created[1].

Using the comments section, authors can reply to users' questions and novice practitioners can learn from previous experiences and questions already posted [40]. Comments were also the place

where modifications were requested. In a study done by Alcock et al. [1], comments were related to adapting existing designs in about 24%, with a split of 86 % related to changing a design's functionality and 14 % aiming to improving printability.

2.2 Varying degrees of innovativeness

As stated by the authors of a recent study of innovation on Thingiverse.com [17], reusing existing knowledge is indispensable for the creation of novel designs. Although there is no lack of definitions for innovations, there is a consensus that innovations imply a discontinuity or disruption:

- either in the way a novel product addresses an existing problem or user need or
- because a new, parallel market place is developing, e.g. electronic typewriters, smartphones and currently e-cars can be seen as products disrupting existing markets[18].

This view is very much in line with Schumpeter's classical definition of innovation as 'new combinations of production factors' leading to the creative destruction of incumbent products or production methods. Replacing the incumbent is then less a matter of price - minimizing costs - but it is a capability driven process, i.e. offering new features or better performance [36].

For our current discussion of remixing behaviour specific to a sharing platform of 3D-models the question is whether remixed models include 'new features' or show 'better performances'. For that to answer, it is helpful to have a more fine-grained typology of innovations. A common categorization includes 2 dimensions [18]:

- micro versus macro level innovations (referring to the scale of impact, i.e. is it an innovation to a single firm or an entire market) innovations and
- the innovation's power to disrupt technology and market directions.

According to the authors in [18], radical innovations include macro level discontinuities, affecting markets and technologies, and incremental innovations are micro level discontinuities, where it is sufficient if either technology or markets are affected. Hence, the questions we need to add to our research agenda are: 'What added value do users have of remixed designs?' and 'Does this value originate from a model's features or is it more the associated production process of the model that creates the value?'. For example, a 3d model with additional functionalities might exhibit better use qualities, whereas a customizable 3d model drastically simplifies the remixing process (*production process*).

3 RESEARCH OBJECTIVES

Being an open platform, Thingiverse.com encourages sharing of 3D models under a Creative Commons license, meaning that all designs can be altered and reused. The ease with which a design can be adapted or remixed is critical in driving the maker movement, where you do not invent from scratch but reuse existing, partly proven solutions[4]. Other features determining sharing and collaboration patterns include the possibility to easily credit original sources, a positive community spirit which supports newcomers and the general usability of the sharing platform, including design

categories, detailed search functions or the featuring of high quality designs. Of course, remixing can take different shapes, such as merging two designs, extracting a specific part from a design or simply slicing a design so that it fits a smaller printer chamber or leads to a less error prone printing process. And there are questions that go beyond dyadic relationships between 3d models, such as how often a remix has been remixed, leading to chains or networks of models forming increasingly complex prints.

While there is consensus on the importance of sharing designs in the maker movement, this is less the case for other aspects such as licensing models, e.g. creative commons with or without commercial derivatives, or the way remixing is supported best, e.g. by creating a customizable model or by referring to the original CAD files. Customizable models are parametric designs where some characteristics can be changed without any knowledge of the underlying programming language. Typically, users change the dimensions of an object or the writing on things like key chains. The creation of customizable models is supported by Thingiverse though its Customizer App. The introduction of the Customizer App had a huge impact on the number of designs hosted on Thingiverse. The year after the introduction, content on Thingiverse almost tripled [28]. However, Blikstein [10] argues that the 'key-chain syndrome' should be of no surprise, since a relatively high 'product value' is achieved with a relatively low 'investment in learning'. Our interest in remixing activities on Thingiverse is primarily motivated by our interest in exploring the platform's potential to provide content in a way that supports educators. The underlying hypothesis is that a model, which has been remixed, has already shown its printability. However, screening the first remixes we quickly realized that this assumption would be incomplete. Thingiverse featured very different types of remixing behaviours, some of which would lead to very innovative, novel outcomes whereas others would mimic the original design with only minimal changes.

Hence, we established three research directions to obtain a more differentiated understanding of remixing:

(1) What is the extent to which remixing is already happening? Exploring different statistics, are there any attention-grabbing characteristics of remixes? In what ways is the number of sources being remixed related to the innovativeness of the remixed product?

(2) What role do other network activities play? Here we are interested in users' liking or downloading behaviour, or the way remixing stays within or transgresses nominal design categories.

(3) Finally, can we go beyond the analysis of dyadic remixing relationships, identifying chains of remixes in the quest for more complex innovations.

Similar questions have been studied bevor, hence the following section will clarify some underlying concepts and assumptions guiding our interpretations.

4 METHOD AND DATA

This paper explores data which have been collected through the official Thingiverse API [22] during the first 2 weeks of November 2017. The data set comprises 893,383 designs (hereafter also referred to as things or 3d models), which have been provided by 193,254
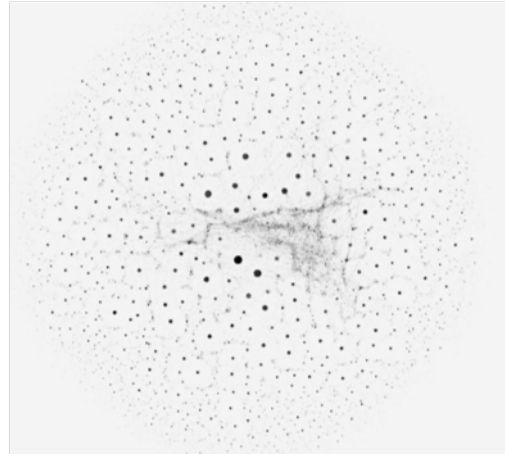

Figure 1: Remixing relationships between designs (n=893,529)

authors. This reflects an almost complete set of designs as far as designs have been published and were accessible through the API.

In network terms designs are nodes which are connected if design R-(emix) uses information coming from design O-(riginal), or put differently R is a derivative or remix of O. It is important to clearly state the technicalities, i.e. on what grounds such a relationship can be established. For example, if the original model is a customizer, then a remix connection with O is automatically established, clearly indicated under the platform's 'remixed from' section. However, if a user decides to download the SCAD (Solid 3D CAD) file of a design, modifies it and uploads it again, then he or she is strongly encouraged to list the original, but there is no technically enforced mechanism for tracking the remixing of existing models. Similar issues with attribution have been explored within the Scratch programming community, showing that even automated crediting is not sufficient if users feel that a remix is more an act of plagiarism than of remixing, especially if the 'remix' consisted of a minor change of colour [25]. This implies that the connections between designs need to be seen as an approximation, either because remixers did not credit the original author (false negative) or because a claimed remix is in essence a copy (false positive)[27].

Figure 1 shows the complete graph of Thingiverse designs, using Gephi's force-directed layout[7]. The high number of nodes shown only allows for a low resolution of network relationships. The figure shows 893.529 nodes, which are clustered in 403.096 components (i.e. groups of linked nodes). Within those components the connectivity is largely low as indicated by a mean clustering coefficient of 0.0057. A cluster coefficient of zero indicates a star graph and a coefficient of 1 refers to a complete graph.

A more meaningful way of looking the structure of the network is presented in Figure 2. Here we can look for a network's uniformity or assortativity (e.g. the correlation between the degree of a node and the average degree of its neighbours). The Thingiverse network is dissortative for nodes with less than 10 connections, i.e. designs with few connections are linked to designs with many connections. A reflection in line with the low clustering coefficient.
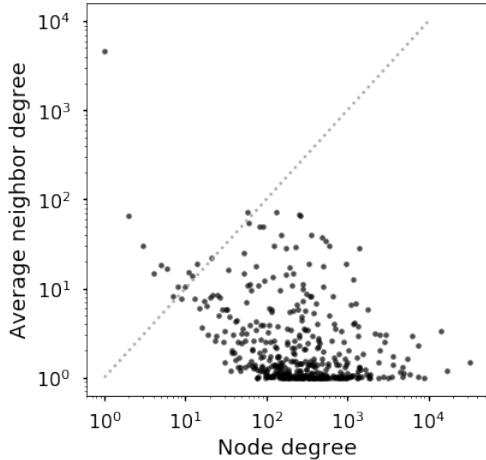
Figure 2: Nodes' degrees and average degrees of neighbours

Table 1: Remixing on a user level (u=193,254)

Remixing Variable	Mean	SD	50%	95%	Max
Users remixing activities	2.5	14.0	1	10	4,485
Users own designs being remixed	2.5	137.0	0	2	37,092
Number of designs per user	4.6	13.1	2	16	2,199

Table 2: Remixing on a design level (n=893,383)

Remixing Variable	Mean	SD	50%	95%	Max
A design has been reused	0.56	0.59	1	1	29
Number of designs being integrated	0.55	49.55	0	1	32,923

The reverse situation, called homophily and referring to a node's propensity to connect with similar nodes, is only given along the dotted line, on which the original nodes have as many connections as their neighbours. In social networks for examples, we see more homogeneous groupings which counteracts the diversity of the maker community [42].

As of November 2017, there were 499,750 connections between designs, showing a 'heavy-tailed' distribution of remixes, resembling a log-normal distribution (Figure 3).

The figure shows three probability density functions, with the continuous line indicating the degree distribution of the Thingiverse network, the dotted line shows a powerlaw distribution and the dashed line shows a log-normal distribution. The approximation to a powerlaw or log-normal distribution is in so far interesting, as it implies a number of assumptions as to how networks evolve, e.g. well connected nodes attract even more connections [6].This way attractive designs turn into hubs, getting most of the attention of peers, who can decide to contribute to or further elaborate a design.

The power law fit of the degree distribution has been tested as described in [11] using the power law python package [3]. The practical implication of 'heavy-tailed' distributions can be circumscribed with the 'rich get richer model' of growing networks, i.e. nodes which already show a certain popularity are more likely to attract remixes than nodes which have only a few connections yet, a mechanism also called 'preferential attachment'[5] .

For a more in-depth analysis, each node of the Thingiverse network has a number of attributes including 'author', 'design category', 'views', 'likes', 'collected', 'downloads', 'license' and 'self-citation'. Most of these attributes are self-explanatory: 'author' refers to nicknames, not real names; 'collected' indicates the number of times a design has been included in another user's collection and 'self-citation' indicates the number of times a design was remixed by its own author.

For analysing the dataset, we use a mix of descriptive statistics and graph analytics (for indirect effects). The fitting of the distribution of node degrees is an example of the former and analysing the topology of remixing behaviours, e.g. chains of remixes, an

example of the latter. Throughout the paper we make an effort to avoid potential misunderstandings by clearly stating the intent and scope of the underlying research question, how that intent matches the nature of the empirical evidence captured in the graph and what that means for the resulting network patterns or network parameters.

5 A NETWORK VIEW ON THINGIVERSE

The first parameter we were interested in, was the number of remixes happening and whether people whose designs got remixed a lot were also remixers themselves. As shown in Figure 4, there is a substantial difference between the users who remixed most (e.g. 'shivinteger' with 4,485 remixes) versus a user such as 'wstein' who engage in very little remixing but whose designs got remixed about 37,092 times.

Looking at the distribution of remixes on a design level (Table 2), we see a distinctive difference between the number of designs that
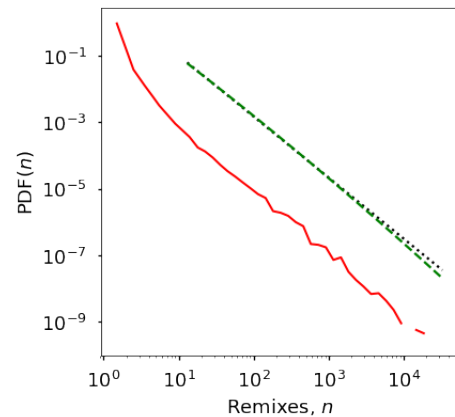

Figure 3: Probability density function of remixes and fitted log-normal distribution.
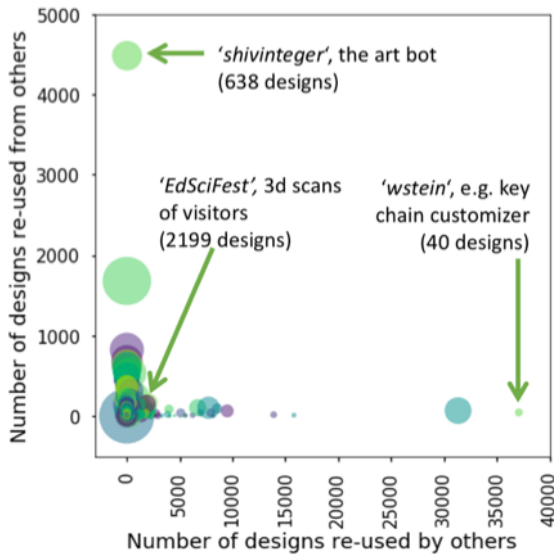
Figure 4: Remixing relationships between designs (n=893,529).

Figure 5: Remixes of two of the most remixed designs with more than one connections.

get remixed (29) and the remixes a design can attract (32,923). In fact, the design including 29 others is a typeface composed of objects from Thingiverse itself, so it is more like a collection of several designs. Whereas the second highest import of designs (26) results in an artistic Buddha figure integrating stylistic elements of movie characters, such as Yoda and Batman. Designs which could attract huge numbers of remixes are largely customizers for key chains (thing ID: 739573) or lithopanes (thing ID: 739573), which are photos transformed into a 3d print, which, if backlit reveal the image. For example, the second most frequently remixed design is a lithopane customizer provided by MakerBot, the company that owns and runs the Thingiverse platform. For this particular case, also the downside of a customizers becomes apparent, the customizer version of this design was repeatedly broken, causing docents of complaints in Thingiverse's discussion forums. The issues could be circumvented by using the off-line application of openSCAD, which is open source [29], but without the ease of remixing within an on-line application many users felt lost.

Both tables and Figure 4 fit findings, which state that there are two distinct groups on Thingiverse, one that almost never uses customizers and one that almost exclusively relies on customizers for remixing[17].

5.1 Customizers, Bots and self-referential designs

A second question we are interested in, was whether remixing is an indicator for a design's innovativeness. Referring back to section 3.2, where we distinguished between product and process innovation, we would classify remixes of highly popular customizers as process innovation.

Key benefit is the intuitive adaptation of an existing design in a prescribed way. Even though it would be possible to remix a remix
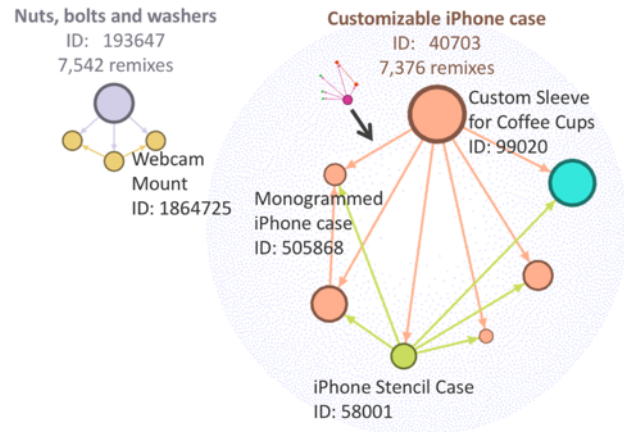
into a novel, improved product, this has rarely happened among the top 6 most remixed designs (representing 9.8% of the total Thingiverse network captured), Figure 5 shows two customizers and their remixed remixes, i.e. nodes with more than one connection. The size of the nodes emphasizes the number of connections and the colour indicates different design categories. The 'nuts and bolts' design has been uploaded under the design category 'parts' and was remixed in the '3d printer accessories' category. Just like the iPhone case has been also remixed in the 'kitchen & dinning' and the 'accessories' category. Behind the iPhone graph the amount of 7,376 nodes, to provide a visual impression of the proportions between the number of times the iPhone case was integrated into a novel design versus the number of times the design was replicated.

As stated in section 2, design ideas coming from outside the Thingiverse ecosystem could enriched the design of an iPhone case as well, but these ideational imports are rarely explicitly documented. Another source of 'noise' within the network's remixing topology are bots. Although not yet as endemic as in the Twitter community, where the followership of prominent figures consists to 20-30% of social bots[13]. In today's highly interconnected world, Bots tampering with the social web can influence public debate by manipulating the perception of reality among users unaware of how much social media are infiltrated by bots [16].

Thingiverse's most prominent bot is 'shivinteger', with 4,485 remixes (some 0.9% of all network connections), leading the list of the most prolific remixers. Unlike some of his Twitter counterparts, shivinteger's purpose is not to manipulate the 3d printing community, but to produce media art. Randomly selected designs are cobbled together, generating bizarre mash-ups which are then uploaded again. The bot's creations have since been presented at art events and generated a discussion about whether bots can create art or whether their art is in fact spam, as it interferes with search results[26].

A third phenomenon we discovered were 'self-citations', i.e. if the authors of the remix and the remixed designs were the same users, then this was counted as self-citation. This could often be seen if users iterated over their own designs, reacting to user comments,
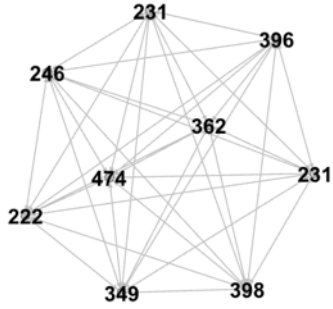
Figure 6: The complete graph of a nine pieces marble race track (Thing ID: 61049 by user 'cassandra').

Table 3: Views, downloads, likes and collections (n=893,383)

Thing Variable	Mean	SD	50%	95%	Max
Views	927	5,883	128	3,619	912,276
Downloads	255	1,542	52	915	342,708
Likes	18	145	1	62	18,248
Being collected	23	289	1	83	220,309
Being remixed	0.55	49.55	0	1	32,923

Figure 7: Spearman - Correlation matrix (n=873,875).

e.g. providing a model with higher resolution or functional changes. Self-citations were also used to indicate a collection of models that belong together, like a nine pieces marble race track (Thing ID: 61049 by user 'cassandra'). Figure 5 shows the complete graph of the track's nine building blocks, where each element references every other element (numbers indicate downloads).

All in all, self-citing was not a very widespread practice. Only 0.013% of all models (12,389) got remixed by their own authors. The two designs that had the highest number of self-citations (12) were a collection of polyhedral wireframes (ID: 282868) and a printed book of bas-reliefs from the Art Institute of Chicago (ID: 463657). The first example presented a collection of similar things, their author wanted to provide as a single download. Overall, we could see multiple cases where the remix was not primarily about changing or adding actual design elements, but it rather was about increasing the convenience of the reusing process, i.e. having related designs in one place or providing STL files when only SCAD files were available. From a novice user's perspective, SCAD is not as straight forward to print then STL, since it still needs to compile and generate the STL (accepted by most additive manufacturing tools) [19].

5.2 A fragmented view: Views, downloads, likes and collections

Part of our research objectives was to explore the interplay between different activities (viewing, downloading, liking, categorizing etc.) and their impact on remixing. By that we want to revisit the boundaries of our interpretations drawn from a network perspective. As stated earlier, networks are based on decisions about what to in- or exclude, and hence they present an incomplete view of the real world. For example, we use the explicit credits given on a design's Thingiverse page as a proxy for real world remixing behaviour.

Table 3, however, shows remixing in comparison to other platform activities. Where we can see that, like remixing, all variables are heavy-tailed.

Hence, given the lack of normal distribution, we used Spearman's correlation coefficient (Figure 6). Due to the extreme values (outliers) of some designs (cf. Figure 3), we discarded the first and last percentile (resulting in 19,508 designs discarded) before calculating the correlation coefficient. First, we can see high correlation coefficients between 'views' and 'downloads' as well as between 'likes' and 'collects'. But what is also apparent, is the very small correlation between out-degrees (i.e. out-degrees are remixes in network analytical terms) and all other variables. We suspect that an influential variable, i.e. a design being a customizer or not, is missing - as it was not available through the API. But as previous research has shown, customizers are much more likely to be remixed than other designs, regardless of their visibility ('views') and appeal ('likes') [17].

A similar discrepancy between views, downloads and remixes can be seen, if we look at the case of a specific design category in Thingiverse. To obtain a network of a reasonable size, that could also be visualized and interpreted qualitatively, we chose a subsection of the 'Chess' design category, with 242 designs (Figure 7). The color of nodes varies with the number of 'remixes' a design got, the darker a node the more 'remixes' it has (see Table 4 for some concrete values). The size of nodes is used to demonstrate a node's relative change in importance when (a) we look at a node's size indicating 'views' - right side of Figure 7 - and (b) when looking at size indicating 'downloads' on the left side of Figure 7.

Again, independently of 'remixes' indicted by colour, we see:

- Design b has relatively few 'views', but then it shows proportionally more 'downloads'. For design c, the reverse situation is shown. For both designs, however, the number of remixes is low (1 remix in total).
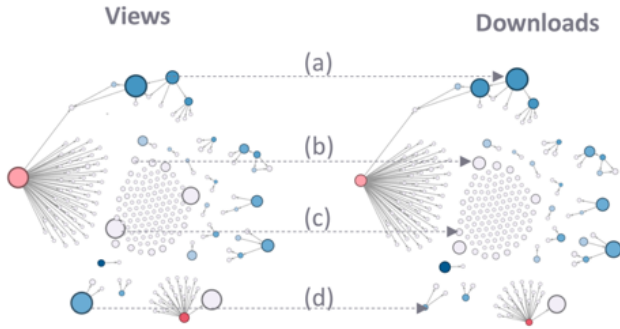
Figure 8: Views, downloads and remixes within a network of chess related designs (n = 242).

Table 4: Views, downloads, likes, collections and remixes for selected nodes

ID / Views	Downloads	Likes	Collections	Remixes
ID: 1732292				
62,199	8,804	2,717	2,665	55
ID: 224664				
22,663	3,193	505	558	21
(a) ID: 1482617				
66,882	15,584	2,320	2,212	6
(b) ID: 18070				
11,820	9,615	107	141	1
(c) ID: 578700				
58,053	3,432	237	221	0
(d) ID: 143991				
66,016	21,366	1,534	1,772	5

- Designs a and d, however, show the same proportional changes in downloads and views, showing relatively more remixes (11 remixes in total).

All 4 designs (a-c) represent sets of chess figures, based on either classic motives or designs inspired by Pokèmon or Minecraft.

Below an overview of each node's attributes as discussed in Figure 7. The red nodes, are 'customizers', and we can already see that they have two or four times as many remixes than non-customizers in the table.

Putting this discussion in perspective with previous studies, a similar average of 14.8 likes [1] was found previously, compared to 18 likes (Table 3). Also, [17] did not consider dynamic variables such as 'views' and 'downloads', but rather derived a regression model including variables such as 'customizer status', 'self-citations', 'days since publication' and 'number of tags'.

5.3 Innovation chains

Understanding not only the dyadic relationships between designs, but also pathways and chains of innovations (e.g. the topology of sub-networks) can benefit our understanding about category spanning innovations, iterative design processes and the integration of multiple ideas.

- Remixing ideas across design categories: This pattern is related to the non-disciplinary nature of user communities as described in Hippel's 'Democratizing innovation' [43]. The underlying rational is that users' innovation behaviour is not restricted by pondering about the commercialization potential of an innovation. Moreover, users, including companies, tend to represent a wide diversity of background knowledge they can bring to the innovation process if needed. Additionally, cross-category innovations tend to explore different contexts and can thereby overcome the limitations of contextually localized search, tapping into spatially confined knowledge [2, 15].
- Iterations over the same design: Iterations are typical for prototyping processes. The interaction with the actual prototype opens up the design space and directs users to possible areas for improvement. The actual experience of using a physical prototype or going through an actual prototypical service arrangement, goes often beyond the original product or service specification [12]. Schön [33], referring to the role of reflection in designing, explains how materials 'talk back to the designer' and that the materiality of a design is a critical in determining whether a design is accepted or not.
- Remixing of more than one original idea: Although we do not assume that remixes of 4 designs are necessarily more innovative than remixes of 2 designs, the nature of innovation (disruptive versus incremental) relates to the breadth and depth of remixing existing knowledge from diverse sources[15, 17]. Enkel and Gassmann discuss cases, where the ropes of mountain climbers help to innovate elevator cables or where 70% of a car engine are reused to design a less fuel demanding engine for small business air-crafts [15].

In Figure 8 we use the example of 'stereographic projection' to illustrate how a mathematically inspired design (1), can spur novel designs across multiple categories, including a projector (2) and a lamp (3). First, 'stereographic projection' is a process for mapping a spherical model to a straight-line grid on a plane, a 3d-model exemplifying this mechanism is the seed for the activities we see below.

At the center is node 202774 (green), whose author provides a collection of designs, visualizing mathematical concepts such as pattern formation, four-dimensional spaces or stereographic projection [34]. All red nodes (e.g. 2094215) are remixes of a mathematical principle, integrated with a projector design and a LED lamp, so that photos transformed into 3d surfaces could be projected against a wall. Whereas the centre node has a moderate amount of remixes (36), the project design has more than 200 remixes for one version alone. This is the effect of providing a customizable projector where each user can upload a photo and generate his or her personalized picture projector. Finally, the design of the picture projector is remixed with a skull (from the 'biology' design category).

6 CONCLUSION

The present analysis has shown the variety of remixing behaviours in a network as large as Thingiverse. Introducing varying degrees of innovativeness, we distinguished between feature-driven innovations and production-driven innovations, whereas customizers are
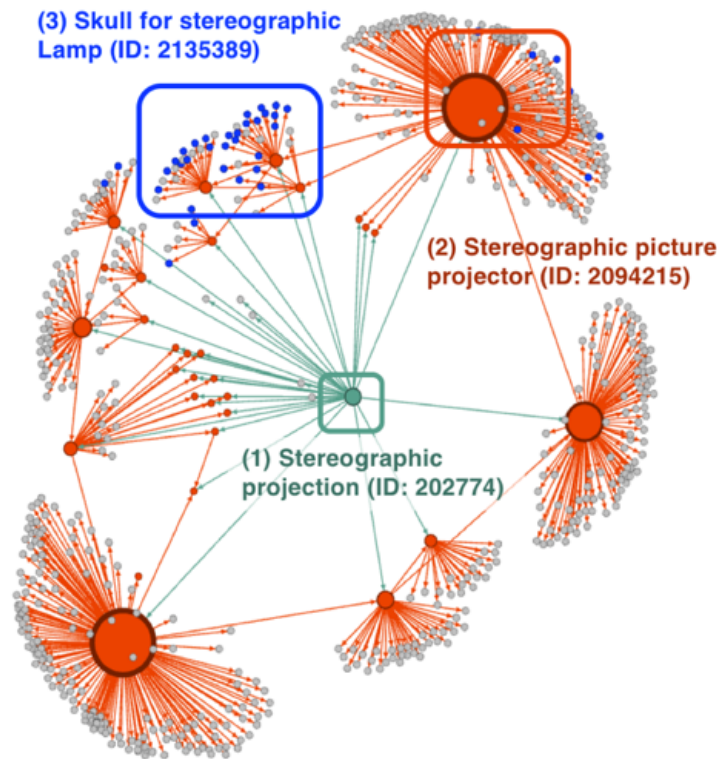
Figure 9: Innovation chains around stereographic projection

an example for the latter. Some of the dominant patterns, such as the huge number of remixes attracted by customizers are technologically induced, i.e. through the provision of a customizer app, which dramatically simplifies the remixing process. Other patterns, such as bots and self-referential designs are less frequent, buts still show the limits of interpreting re-combinations of designs as innovations in the sense of increasing the usefulness of a product or improving a tangible feature of a product.

However, for educational purposes, more complex chains of innovation as describe in the previous section support constructionist and experiential learning more directly, through the need to reiterate, adapt and ensure that the physical product actually fulfils the promises of the conceptual design. In that sense, platform users generating more complex remixes learn to respond to the constraints imposed by the use of specific materials and tools. In the end, complex designs not only promote technical competencies but also personal traits such as self-efficacy (being confident in one's abilities) or creativity (being resourceful in the face of adverse circumstances)[23]. Hence, knowing how to identify topologically more complex chains of innovation will help to avoid the trivialization of 'making', also known as the 'keychain syndrome', which refers to the fact that keychains are among the most remixed designs [10]. Yet, going a step further, from the platform owner's perspective, introducing the customizer was a huge success, as it almost tripled the number of designs hosted. Whether or not, future Thingiverse features will allow for distinguishing between trivial and complex innovation chains remains to be seen.

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