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CASE STUDIES

Patterns of Participation and Motivation in Folding@home: The Contribution of Hardware Enthusiasts and Overclockers

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Folding@home is a distributed computing project in which participants run protein folding simulations on their computers. Participants complete work units and are awarded points for their contribution. An investigation into motivations to participate and patterns of participation revealed the significant contribution of a sub-community composed of individuals who custom-build computers to maximise their processing power. These individuals, known as "overclockers" or "hardware enthusiasts," use distributed computing projects such as Folding@home to benchmark their modified computers and to compete with one another to see who can process the greatest number of project work units. Many are initially drawn to the project to learn about computer hardware from other overclockers and to compete for points. However, once they learn more about the scientific outputs of Folding@home, some participants become more motivated by the desire to contribute to scientific research. Overclockers form numerous online communities where members collaborate and help each other maximise their computing output. They invest heavily in their computers and process the majority of Folding@home's simulations, thus providing an invaluable (and free) resource.

Keywords: distributed computing; motivation; community; enthusiast; overclocking

Recent improvements in information and communication technologies have contributed to an increase in the accuracy and productivity of scientific instruments and data storage technologies. This has led to what has become known as the "data deluge," which has had important implications for citizen science. As some scientists have realised that they will never be able to analyse all of their data on their own, they have devised new ways and projects to enlist the help of those outside of their institutions (Schawinski 2011). Widespread access to the Internet also means that scientists have access to many thousands of potential participants for their projects (Hand 2010). Thus, online (or virtual) citizen science projects that are conducted entirely through the Internet have rapidly increased in number (Curtis 2015a).

The first online citizen science projects were distributed computing (DC) projects such as SETI@home (the Search for Extra-Terrestrial Intelligence) and GIMPS (the Great Internet Mersenne Prime Search). In these types of projects, participants download software that enables their computers to run simulations, or install algorithms that look for patterns in data. No expertise or active input is required of participants, and the project programme generally runs in their computer's background. Participants—both individuals and teams—are awarded points for completed work packages, which introduces a competitive element, as leader board display top contributors. Online forums provide information about the projects and advice on running and downloading the software. They also provide opportunities for participants to discuss other related (and unrelated) topics.

Approximately 60 DC projects are currently active in a variety of scientific disciplines, with hundreds of thousands of participants worldwide. One of the first DC projects in the biological sciences was Folding@home (https://foldingathome.stanford.edu/), which is based in the Chemistry Department at Stanford University in California (Sansom 2011). The project was developed in October 2000 by Professor Vijay Pande, whose group continues to manage it (Beberg et al. 2009).

Folding@home was developed to help understand the process of how protein molecules fold into their final 3-dimensional structure. In the cell, protein folding occurs incredibly quickly, within milliseconds or microseconds. Folding@home enables the folding process to be simulated at a rate thousands to millions of times slower than it naturally occurs. The simulation allows scientists to examine protein folding more closely and to study aspects of folding that cannot be studied easily in laboratory experiments. Currently the Folding@

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home team and its collaborators are investigating protein mis-folding in relation to cancer, Alzheimer's Disease, Parkinson's Disease, and brittle bone disease (among others). So far, 159[1] papers have been published based on the project's output.

Approximately 100,000 computers or CPUs (computer processing units) are running Folding@home (although this fluctuates). However, this does not equate to the number of project participants, because some individuals run the programme on many machines and use multiple processing units. Exactly how many participants are involved in Folding@home is difficult to know. One third-party website that regularly monitors Folding@home output[2] suggests that it may be in the region of 28,000.

Participants can view their progress through the various work packages via a pop-up on their web browser (**Figure 1**) or a screensaver (**Figure 2**).

Previous research on DC projects

Given the large number of participants in DC projects (and the resulting publication output), patterns of participation and motivation to participate are of interest, not only to those who set up and manage projects but also to those interested in increasing access to research and opening up participation to non-specialists. As big data and associated projects continue to be of importance, DC projects have the potential to involve and engage many more citizens with research. Compared with other types of citizen science projects, there is a much smaller body of work relating to DC. This is especially true in relation to patterns of participation and its appeal to computer hobbyists.

Previous research suggests that DC appeals to a specific demographic. Four published studies and two project surveys have provided some information about the characteristics of DC participants (Estrada et al. 2013; Holohan and Garg 2005; Kloetzer et al. 2016; Krebs 2010; SETI@home, 2006; World Community Grid 2013). These are summarised in **Table 1**. One of the most notable observations is that a large percentage of the participants surveyed are male. Half of these studies also found that a significant proportion of survey participants work in information technology.

Five studies have considered motivation to participate in DC. In the earliest of these, Holohan and Garg (2005) explored motivation to participate in two projects, SETI@home and GIMPS. Their work suggests that study participants were motivated mainly by the opportunity to make a scientific contribution, followed by the enjoyment they derived from competing with other participants. The researchers also observed that study participants differentiated these two main motivations and appeared to present "official" reasons for taking part which were more altruistic and based on contributing to research, and "unofficial" (or perhaps less worthy) reasons that were based on competing with others for points. Another important motivator was the social aspect of participation, including the interaction with other participants and the sense of community that could develop among teams.

Nov et al. (2010) conducted a survey of 274 randomly selected SETI@home participants. These authors linked survey findings on motivation to actual levels of participant contribution as determined by their activity logs. They considered intrinsic motivations (such as personal interest and enjoyment) and extrinsic motivations (such as rewards in the form of points), and also whether these motivations were "self-oriented" or "project oriented." They found that "self-oriented" factors relating to personal enjoyment and enhancement of reputation were important motivators but were not statistically related to contribution levels. However, being affiliated to a team was positively related to contribution levels, suggesting that being in a team leads to greater levels of participation.

Krebs (2010) looked at the motivations of participants in MalariaControl.net, a project where participants' computers run epidemiological models of malaria infection. She also looked at the motivations of a smaller group of participants who participate in BOINC (Berkeley Open

Figure 1: Folding@home progress page. Participants can track the completion of a current project and find more about the scientific aims. They can also select what disease they wish to work on from a pull-down menu (authors own account).

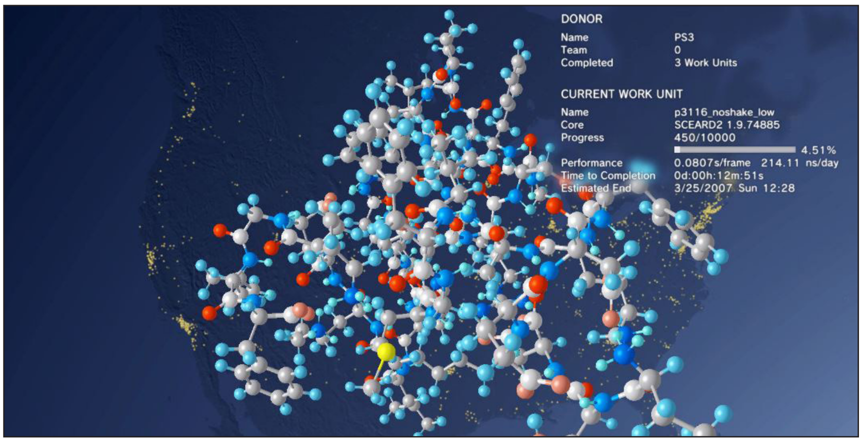

Figure 2: Folding@home screensaver showing protein folding simulation.

Table 1: Demographic data of citizen scientists involved in DC projects obtained from six published studies or surveys.

Author/year	Project and sample size	Demographic details of sample
Holohan and Garg 2005	Various distributed computing projects including SETI@home and GIMPS (Great Internet Mersenne Prime Search), **n = 323**	98.4% were male, and most aged 26–49. 70% based in USA and Canada, and 24% based in Europe.
SETI@home team, 2006 online member survey	SETI@home, **n = 142,000**	92.74% are male, and 61% were aged 20–39.
Krebs 2010	malariaControl.net, **n ranges from 693 – 1,097**	56% were based in Europe and 33% in North America. Most were aged 20–50. 87.8% were male (n = 693). Most survey participants were IT professionals.
Estrada et al. 2013	Docking@home, **n = 739**	80% were male, and most males were aged between 31and 35. Female respondents were aged mainly 46–55. Small representation of "ethnic minorities."
World Community Grid member study 2013	World Community Grid collection of distributed computing projects, **n = 15,627**	90% of sample was male, and most have a "technical knowledge base." Most aged 25–44. 36% work in information technology.
Kloetzer et al. 2016	Alliance Francophone, BOINC community, **n = 147**	93% of sample was male. Two-thirds were aged 26–45. 23% work in the field of computer science. Varying levels of post-secondary education.

Infrastructure for Network Computing)[3] distributed computing projects. Using a previously developed list of 10 potential motivations, Krebs found that wanting to contribute to a community and getting involved in a particular cause (such as helping to advance understanding of a disease) were the most important motivators. These two motivations were also the most important for the group of general BOINC participants. Less important for MalariaControl.net participants were extrinsic motivators relating to enhancing professional experience, networking, learning, and knowledge sharing. Krebs' study also suggests that recognition of a volunteer's contribution is important, and many respondents stated that providing tangible rewards (e.g., points) was important.

Motivation to participate was explored in a large survey of participants in the World Community Grid, a collection of distributed computing projects overseen by the IBM Corporation which focus mainly on humanitarian issues such as cancer epidemiology, the search for disease biomarkers, and carrying out research calculations on potential drug candidates (World Community Grid 2013). This survey of more than 15,000 participants found that almost 70% of respondents participated because they want to support scientific research in important areas of health. The next most important reason (cited by 58%) was to make use of their unused computing power. The fact that all the results generated through the World Community Grid are publicly available was important to some respondents.

A small qualitative study carried out by Darch and Carusi (2010) of 35 Climateprediction.net participants considered ways in which participants could be retained. These researchers found that some participants contributed a great deal more than others. This group was referred to as "super-crunchers," who were strongly motivated by the competitive element of the project. The authors concluded that maintaining an acceptable reward system based on points would be the best way to retain these participants over time.

Finally, a recent study by Kloetzer et al. (2016) explored engagement and learning in the Alliance Francophone DC community and found that an interest in science and computing can motivate participation, and that opportunities for learning can lead to sustained participation. This study also found that a small group of participants was involved in other project tasks such as managing community forums, promoting the project, or preparing FAQs for new users.

While this work provides some insight into motivation to participate in DC and suggests who the projects may appeal to, gaps remain in our understanding. This is particularly true in relation to patterns of participation and the appeal of DC to specific groups. There is evidence that participation in other types of online citizen science projects, particularly in distributed thinking projects such as those on the Zooniverse platform, is uneven, with small groups of participants doing the majority of the work (Ponciano et al. 2014). The work of Darch and Caruso (2010) suggests that a similar pattern may exist in DC, but the question requires further investigation.

To investigate patterns of participation in DC in greater detail, I spent eighteen months exploring Folding@home. I conducted surveys and employed qualitative methodologies such as interviews and observations. I was particularly interested in sub-communities known as overclockers, because their activity and contribution have not been highlighted in previous research. I addressed the following research questions:

1. What are some of the broader demographic characteristics of Folding@home participants?
2. Why do people participate in Folding@home?
3. Do participants contribute to the project in the same way?

Methods

I selected Folding@home for an in-depth case study because it is well established, has a sizeable community of participants, and has resulted in many publications (a marker of success for some). In addition, the project scientists wanted to find out more about their community of participants.

A case study focuses on one thing: An individual; an organisation; an event; or a project, which can be examined in depth and from many angles. Case studies are employed to gain a rich picture of real-life circumstances to obtain analytical insights (Gillham 2000), and they use multiple sources of evidence and lines of enquiry to provide a "chain of evidence" for addressing research questions (Thomas 2011). This study included three different data- collection streams: Observation of participants (through project forums, blogs, and hobbyist forums), an online survey, and semi-structured interviews.[4] Initial observations of the project community informed development of the online survey, while the results of the survey, as well as ongoing observations, informed the interview questions. Data were collected during 2013 and 2014.

Numerous online communities are associated with Folding@home, including the official Folding@home community forum on the project website as well as third-party or team forums that are organised independently. Thousands of participants interact online, and hundreds of archived discussion pages can be accessed freely and searched. Some of the external teams were identified through the project leader board, and I was able to observe wider interaction among participants. The content of discussion threads was explored and relevant themes and material were recorded in the form of field notes and screen shots. This material was examined for emerging themes and subsequently used to triangulate the findings from the online survey and interviews. Many of these discussions were especially illuminating with regard to the motivations of sub-communities of participants. For example, the EVGA team discussion forum has a thread entitled 'Why We Fold," with hundreds of responses dating back from 2010. One of the advantages of exploring online citizen science projects (especially those with community forums) is that a rich and readily accessible source of information about the project is often available.

The online survey contained a mixture of 28 closed- and open-ended questions and was constructed using the Bristol Online Survey tool (Appendix A, supplemental materials). The survey was tested and reviewed by the Folding@home project team before it was launched on the Folding@home website. Survey questions were informed by previous research on online citizen science by the author (Curtis 2015a), and an effort was made to collect data that could be compared with data collected by other researchers. However, as this research sought to broaden our understanding of participation, an effort was made to collect more detailed information relating to participant motivation, rewards, patterns of participation, and a wider range of demographic data (e.g., on formal science education, profession, and participation in other science-related activities). Furthermore, the survey had a greater reliance on qualitative questions than in some previous work on online citizen science to provide respondents greater freedom to express their views (Nov et al. 2011; Raddick et al. 2013). A link to the online survey was placed on the Folding@home support forum, including some background information about the research. The same information was provided in the regular newsletter that the project team produces for participants.

Responses to closed survey questions were collated automatically by the survey tool, while the qualitative feedback from the open-ended survey questions was subjected to a content analysis by the author. In content analysis, textual data is explored inductively for emerging themes or "meaning units" that relate to the same central meaning (Graneheim and Lundman 2004). These themes can be grouped into content or coding units, which can then be counted and subsequently expressed and analysed quantitatively. In this study, motivations for participation were identified, counted, and represented graphically.

Respondents were asked to provide their email address in the survey if they were willing to answer further questions about their participation in Folding@home. Observation of online forums and different communities of participants revealed that there was a distinct subgroup that contributed greatly to the project, namely, overclockers and hardware enthusiasts. To identify participants who belonged to this community, I looked for participants who belonged to a team that was associated with overclocking (some teams have "overclockers" in their name, or are affiliated with computer hardware manufacturers). I then verified this by looking at the output on their individual profile page. As overclockers process very large amounts of data, they accumulate hundreds of thousands of points. I contacted 50 overclockers who had provided their email address, and approximately 8 agreed to be interviewed. The interviews were used to explore their participation in more detail and were carried out via email.

The interview responses were subjected to thematic analysis. This is a widely used qualitative analytic method for inductively identifying, analysing, and reporting patterns (or themes) within data. Gillham (2005) defines a "theme" as a horizontal category, something that exists as a kind of "sub-plot" within the main narrative. The identification of themes is thus a form of pattern recognition that allows the researcher to go further, ultimately using emerging themes as categories for analysis. I have followed the comprehensive approach of Braun and Clarke (2006), in which a thematic analysis can be broken down into six separate stages:

1. Familiarising oneself with the data (transcribing, noting, reading, and re-reading);
2. Generating initial codes;
3. Searching for themes;
4. Reviewing themes;
5. Defining and naming themes;
6. Producing a final analysis involving the selection of extracts and relating these back to the research questions.

Results

Participant observations of project and other community forums

Observations made early on in this investigation on the official Folding@home forum (https://foldingforum.org/) helped to highlight the existence of a community of highly active participants who appeared to contribute greatly to the processing output of the project. Firstly, participants on the leader board had collected vast numbers of points of a much greater magnitude than individuals running Folding@home on a single PC or lap-top. As an individual participant, I knew how many points my level of participation would generate, and realised that it would take me decades to be awarded as many points as the leaders. Secondly, I noted that most of the interaction between participants on the Folding@home forum involved highly technical language, often relaying advice regarding getting the "most out of their machines," or solutions to technical problems. These observations were important because they highlighted the fact that like other types of online citizen science projects, a small group of participants were doing the bulk of the "work." They also suggested that participation in DC may not always be as passive as some authors have previously remarked, but may involve greater effort and perhaps specialist knowledge.

A further observation, that many of the Folding@home teams (participants can pool their points and compete with other teams) were affiliated with hardware manufacturers or had the word "overclocker" in their name, helped to identify this community.

Because success on the Folding@home leader board results from very high levels of processing power and output, Folding@home (as well as other DC projects) attracts overclockers, computer hardware enthusiasts who build custom machines with the aim of maximising their processing power (Colwell 2004; Bohannon 2005). Occasionally, individuals (or teams) compete to see whose machine can produce the most processing power, and one way to measure performance is through participation in DC projects. These projects thus provide a "benchmarking" tool for the overclocking community, as well as providing an important data processing tool for scientists. Little information exists about overclockers and their contribution to DC projects, but one estimate states that they may contribute over half of the processing power to all distributed computing projects (Bohannon 2005).

Members of the overclocking community refer to themselves as either "folders" (those who take part in Folding@home) or "crunchers" (those who take part in other DC projects that are based on the BOINC computing platform). Darch and Caruso (2010) refer to "supercrunchers" in their study of Climatepredicion.net, a DC project that runs climate simulations on participants' computers. This group of enthusiasts was estimated to contribute more than 60% of the processing output for the project. Overclockers (including those participating in Folding@home) are also active in other aspects of DC projects and contribute to running online forums and translating project FAQs. They further divide into additional sub-communities that have other common interests such as gaming, science fiction films, writers, or comics. Indeed, one of the largest and most successful teams in Folding@home is Brony@home, composed of adult fans (Bronies) of a cartoon series called "My Little Pony: Friendship is Magic," which is based on the "My Little Pony" toy.

Forum discussions often focus on equipment and machine set-up, and it is apparent that some Folding@home overclockers invest significant amounts of money in their machines or "rigs" (sometimes many thousands of US dollars), and that running them may require a large amount of electricity. Many rigs incorporate multiple processing components requiring sophisticated cooling systems utilising liquid nitrogen. Community members proudly share photos (**Figure 3**), and also boast about the number of points they have managed to accumulate in friendly rivalries.

From exploring hundreds of pages of forum discussions, both on the Folding@home forum and independent team communities, it is clear that overclockers greatly enjoy their hobby. I observed discussions that focussed specifically on the research aims of Folding@home and

Figure 3: Customised "rig." The use of neon lighting and purpose-built display cases add to the aesthetic appeal of the machine (image from the EVGA Folding Forum).

Table 2: Demographic characteristics of survey group (n = 407).

Age	63% aged under 40
Gender	98% male
Education	57% had a university education (80% of these had degree in STEM subject); 20% were currently studying at university. The remainder were educated to high school (or equivalent) level.
Geographical distribution	All based in US, Canada, and Europe with the exception of 11 respondents.

the importance of the work that was being carried out by the Pande Group, particularly on Alzheimer's disease and Parkinson's disease. There are threads where participants talk in detail about the impact that these illnesses have had on their lives. Indeed, some forum areas have become virtual shrines to friends and family members who have been affected.[5] There is evidence of long-term involvement in DC with the same usernames appearing over many months or years. Online friendships are evident, and members of these communities discuss a wide range of subjects that are unrelated to overclocking or DC.

Calculating the number of overclockers who contribute to Folding@home is difficult to do with accuracy. However, I analysed an external statistics site[6] with a list of all the registered participants. Assuming that those with a certain level of accumulated points (in the hundreds of thousands) are able to achieve this only by overclocking their machines, I estimate that approximately 10,000 individual overclockers have contributed to Folding@home at some point since it was launched.

In addition to overclockers, observations of the main Folding@home project forum also revealed the presence of another (much smaller) group with an increased contribution. This was a group of approximately 30 individuals with skills in computer software known as the Beta Testers. They were invited to participate by the project team, and they helped to test new project software and fix bugs (Curtis 2015a).

These observations of Folding@home participants demonstrate that overclockers and their associated communities provide the scientific team with their main source of processing power, and this likely occurs in other DC projects as well. The specialist knowledge and willingness of these communities to invest in hardware has facilitated this research and contributed to nearly 150 publications. Overclockers share knowledge with other members of the community, collaborate with each other, and in some instances, create "communities of practice" that develop a repertoire of resources, experiences, and tools as a way of developing and sharing their skills.

Survey results

Responses were collected from 407 participants. One of the main problems with online surveys is that the response rate can sometimes be low, so it must be emphasised that respondents may not be representative of the total population of participants, and that those who participated are a self-selected sample (Sterba and Foster 2008). Demographic characteristics of respondents are summarised in **Table 2**. Most respondents are in skilled professions (**Table 3**), with a significant proportion stating that they work in an IT-related profession.

The majority of respondents (89%) belonged to a team, with many belonging to one that was obviously related to an overclocking or hardware enthusiast community, for example, Team EVGA;[7] Maximum PC; and Team OCF (over clockers forum). Some belong to national teams of hardware enthusiasts such as Dutch Power Cows and Hardware.no (Norway). Most respondents (79%) also reported actively participating in online project forums—the “official” Folding@home forum and/or their own team forums. Responses to questions about team membership and participation in forums revealed that a small proportion (16.5%) were unaware of the forums, or simply wanted to run the software and not become any more involved in the project.

Nearly half of respondents had taken part in other distributed computing projects with many respondents mentioning SETI@home, the World Community Grid, and Einstein@home (a project that looks for evidence of pulsars). Most respondents demonstrated a wider interest in science and had taken part in science-related activities in the previous year, such as reading online science material or science magazines, visiting museums or science centres, or attending an amateur astronomy event.

When questioned about why they took part in Folding@home, respondents usually provided more than one reason (**Figure 4**), although the most commonly cited reason (25%) was to make some sort of contribution. There appeared to be two distinct types of contribution: Contributing more generally to a “worthy cause” and making a specific contribution to scientific or medical research. Approximately one quarter of respondents referred to the former, with some stating that they viewed their participation as a type of charitable donation—of computer processing power instead of cash. Interestingly, the project team refer to all Folding@home participants as “donors.”

Table 3: Occupation/profession of respondents (n = 403).

IT Professional	150 (37%)
Student	80 (20%)
Business professional	43 (10.5%)
Engineer (not IT)	26 (6.5%)
Science/medical	24 (6%)
Technical/mechanical	19 (4.6)
Unemployed (no previous occupation given)	16 (4%)
Clerical/admin	8 (2%)
Other assorted professions or retired	37 (9%)

The second most commonly cited reason for participation was to fully utilise computing power, and this reflects the presence of overclockers among this group of participants. Fifty respondents specifically mentioned their involvement with an enthusiast community in their response to this question, while many made comments regarding minimal wastage of power or getting the most out of their machines.

Another important reason that respondents participate in Folding@home is because they have had a personal experience with one of the diseases that is being researched through the project, either personally or with a family member. Seventy-four respondents (18%) relate some experience of cancer, Alzheimer’s Disease, or Parkinson’s Disease, and they address a need to take a more “active” role in potentially beneficial research.

Few respondents stated that they joined the project for the community or for the competition, which is surprising given that teams and individuals compete for points. However, in the study by Holohan and Garg (2005), the authors noted that respondents had “official” reasons for taking part, which were more altruistic, and “unofficial” reasons, which were often implied and usually related to the competitive aspect of participation and position on leader boards. This observation may also be of relevance to Folding@home, and support for this was more evident in the interview feedback and from observations of team forums.

Respondents were asked whether they thought that Folding@home participants should be rewarded for taking part, and if so, what would be the most appropriate way to reward them. While a majority felt no extra reward

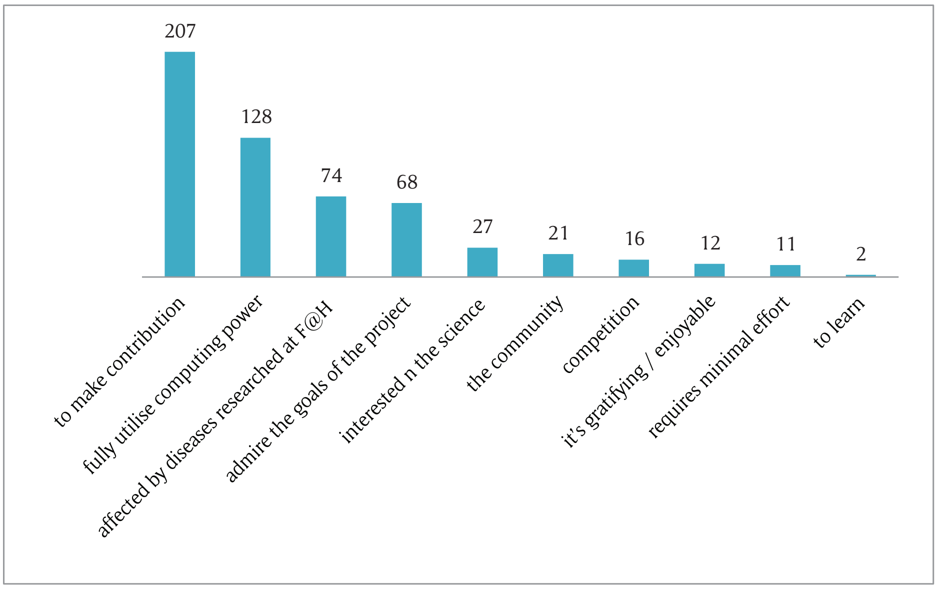

Figure 4: Motivations for participating in Folding@home.

was required, a quarter of respondents would like to see something extra offered to participants and made suggestions as to what that should be. These included virtual badges, better quality certificates (currently participants can download a certificate of participation at any time), tours of the labs for significant contributors, an annual convention for participants, discounts on related computing products, discounts on educational items, cash for reaching a certain level of points, prizes such as Folding@home T-shirts or mugs, or a "user of the day" feature (this is done in other DC projects).

The most commonly suggested reward (made by 31 respondents), however, was to be able to claim their electricity costs as a tax rebate, in the same way that other charitable donations can be offset (this suggestion was specific to US participants). Approximately 20 respondents indicated that they would like to see a greater acknowledgement of the contribution of participants in scientific papers.

Interview feedback

The survey and observations highlighted the major contribution of overclockers to Folding@home. As there is a lack of available data about this community generally, interviews were conducted to understand more about this important group of participants. Eight individuals agreed to take part in the follow-up interviews. They were asked in more detail about their motivations for participating in Folding@home, and specific questions were asked about their involvement in the overclocking community. It should be noted that this sample of survey respondents may be skewed towards those who have stronger opinions about Folding@home and wanted to provide more detailed feedback.

For many of the interviewees, Folding@home gives them the opportunity to push their hardware to the limits, while also contributing to something worthwhile. They can learn about new technology and the application of hardware, which is of deep interest to them. Most respondents enjoy being involved in a larger community working towards a common goal.

> *"The people on this team are great folks—always supportive and willing to help solve issues regardless of what the problem is. If they don't know the answer, they'll help dig and find it. Along with the teammates, just the general folding community."* (Participant 4)

One of the respondents referred to the fact that he was involved in Folding@home because he had a "mission" and a "purpose."

> *"Until everything we are fighting is gone, I will continue to fold."* (Participant 4)

This is a reference to the diseases that the Pande Group seek to understand as part of their research. In the online survey, approximately one fifth of respondents stated that they had been personally affected by the illnesses that Folding@home investigates. This personal connection to these illnesses was also referred to by most of the interviewees, emphasising that for some participants, the long-term goals of the project are of great importance.

> *"Some of my closest relatives have been affected by some of the conditions researched by Folding@home. I wish to contribute in whatever way I can to improve our medical knowledge of these conditions…."* (Participant 2)

Even for those who do not mention a personal experience of the Folding@home diseases, the long-term research goals of the project are recognised as being important.

In addition to processing power, members of this community also contribute by bringing a broad range of technical skills to the project. These skills and knowledge are often shared with other enthusiasts to help them build better machines (usually via team or supplier forums), or by providing advice on what products to buy. Overclockers also share their knowledge more widely with other folders on the Folding@home forum. This community also "spreads the word" about Folding@home, and individuals actively recruit others to Folding@home teams through the overclocking forums and networks.

Overclocking has a highly competitive aspect (Bohannon 2005), and Folding@home (as well as other DC projects) provides a way of testing an individual's skills and knowledge.

> *"I see a lot of competition within the overclocking community as a whole—This is a community that naturally gathers those who love competition and/or those who are obsessed with getting the most out of a piece of equipment, much like those who tune their car engines for maximum performance."* (Participant 8)

Making a contribution *and* taking part in the competitive aspect of participation sit side-by-side for most interviewees. An initial interest in the project motivated by maximising computer processing power can develop into a greater appreciation of the scientific goals of the project. One interviewee referred to this community as being in "two camps."

> *"Generally, I see this group in two camps: A. Those that are folding because of their hatred of disease and wanting to eliminate it from the face of the earth. B. Those that fold because they want to build the best computer they can and tweak and twist it to get every last drop of performance. I started out in camp #2 … but the more I learned about what I was actually getting into, I've migrated to camp #1."* (Participant 4)

One interviewee was not aware of the science behind Folding@home when he first joined the project.

> *"When I first found out that the program was actually doing science and not stress testing, I looked*

> *straight into it and was amazed that we were able to simulate such things."* (Participant 5)

Such statements suggest that motivations in this community are dynamic and can change over time. This has been observed in other citizen science projects (Rotman et al. 2012). While the technical aspects of Folding@home may be a stimulus for initial involvement, more altruistic motivations may operate once participants begin to understand the benefits of the research.

Most of the individuals interviewed had been overclocking for at least several years and spoke of the enjoyment that they derive from being part of a community of like-minded individuals and of the opportunity to learn more about computer hardware. One overclocker described himself as an *"eternal student of technology."* Such feedback suggests that as observed in the work of Kloetzer et al. (2016), learning about new technology is a stimulus for participation and may sustain participation over many months or years.

As overclockers can invest significant amounts of time, energy, and money (in the form of hardware and electricity) in Folding@home, they like to maintain a level of involvement and keep up to date with the project team through the blog and numerous folding forums. Practically all of those interviewed had some opinion about the project team, particularly how the team interacted with the Folding@home community. Several respondents wanted to see better general communication with the folding community and highlighted the need for feeling valued by those in charge of the project.

How points are awarded in Folding@home was a contentious issue for several of these participants. During the study period, the way that points were allocated changed. The reaction and views regarding this change (particularly angry responses on the forums) suggest that some participants are highly motivated by points, something that wasn't obvious in the online survey results. This observation suggests parallels with the work of Holohan and Garg (2005), who identified "official" reasons for taking part which were more altruistic, and "unofficial" reasons which were based on points.

Discussion

This case study has shed light on a key group of participants in a DC project and has provided some insight into who participates, why they participate, and how they participate. Within the broader context of online citizen science, this work also demonstrates that Folding@home has some features in common with other projects such as demographic characteristics, motivations for participation, and variable levels of contribution (Curtis 2015a, 2015b; Masters et al. 2016; Ponciano et al. 2014; Raddick et al. 2013; Reed et al. 2013).

The first research question in this study relates to the broader demographic characteristics of Folding@home participants and is addressed mainly by results of the online survey. This sample of 407 Folding@home participants was almost entirely male. They were well educated, interested in science generally, likely to work in IT, and found mainly in North America and Europe. Through my observations of several overclocking forums there appeared to be few women generally among this community. Several contacts on the forums were questioned about this, and all stated that overclocking tends to appeal more to men, and if there were female overclockers, they weren't present to any noticeable extent on the forums.

This predominance of male participants has been observed in other online citizen science projects, not just in DC (Curtis 2015a; 2015b; Masters et al. 2016; Raddick et al. 2013; Reed et al. 2013). Surveys into public attitudes towards science and technology may explain this finding to some extent. Some research in the UK has shown that men are more likely to engage with science than women, and are more likely to take an interest in new technology and scientific developments (RCUK 2017; Ipsos-MORI 2014). Consequently, men may feel more confident in engaging with these projects. Other research relating to online citizen science projects has reported a high representation of those in IT-related professions (Curtis 2015a, 2015b; Krebs 2010; World Community Grid 2013). Such projects (particularly DC) may hold a greater appeal for those familiar with, and comfortable using, information technology. Women are still outnumbered in this field, which may also help to explain the extremely low proportion of women in the Folding@home sample. Six of the seven female respondents in this study either worked in IT or were computer science students.

In addressing the second research question, why people participate in Folding@home, the data suggest that making a contribution to science (or a worthy cause) motivates much of the participation. This is true for both the more active and the passive groups of participants. This motivation operates in concert with a wider interest in science, which brings individuals to citizen science projects, perhaps instead of other types of volunteer-based activities. The desire to make a contribution is a key motivator in other types of citizen science projects.

The competitive aspect of overclocking and the desire to learn more about computer hardware is also a strong motivator for many active participants. For some it is the primary motivator, which may later lead to an appreciation of the wider scientific context of the project. Participants within the overclocking community are also motivated by the sense of community and teamwork, and some participants form online friendships that last for many months or years. The importance of community has been seen in other citizen science projects, and can help to sustain more active and involved participation (Curtis 2015b; Mugar et al. 2014).

A model to describe motivation to participate in online citizen science is presented in **Table 4**. It is based on a meta-analysis of previous research and informed by other relevant models of motivation relating to general volunteering, participation in online peer production projects (such as Wikipedia and open-source software), and formal education (Curtis 2015a). It incorporates the motivations that have been articulated by individual participants in previous studies (including the respondents from this study) and presents them within a classificatory hierarchy.

Table 4: Motivational framework for online citizen science.

Level 1	Level 2	Level 3	Level 4
Internal Factors	Intrinsic motivations	Enjoyment	Relaxing Visual appeal Fun
		Fulfillment	Background interest in science Participation in authentic research Allows creativity Learning opportunity
		Competence	Intellectual challenge Using skills Formal qualifications not required Different ways to contribute
	Altruism	Making a contribution	Contributing to scientific research Contributing to a worthy cause Helping scientists
	Community	Interaction with others	Work with others toward common goal Make friends
External factors	Extrinsic motivations	"Ego enhancement"	Points Rank Making a discovery Wider recognition Positive feedback from scientists
		Identification	Goals of the project are important
	Expected future returns	Medical/scientific breakthroughs	Research publications New drug therapies and cures

At Level one, motivations can be classified as either internal factors, which are rooted within the individual, or as factors that are external to an individual (Hars and Shaosong 2002). At level two, internal factors can be subdivided into intrinsic factors, altruism and community, while external factors can be divided into extrinsic factors and expected future returns. These can be further subdivided (level three) into a number of elements that have been identified by Ryan and Deci (2000) as the components of intrinsic and extrinsic motivation. A further breakdown of altruism, community involvement, and expected future returns, and their relevance to online citizen science projects, also has been illustrated at this level. Level four represents the highest "granularity" of motivation and, when questioned, most respondents articulate motivations that are either level four or level three. This model may help to understand, as well as classify, motivation to participate in online citizen science, and takes into account the traits that these projects share with other types of voluntary behaviour (Batson et al. 2002).

In addressing the third research question, do participants contribute to the project in the same way, it is evident from the data that they do not. There is a definite split between those who contribute via their interest in computer hardware and overclocking and those who participate in a more passive way by just running the project software. While differences in output have been observed in previous work (Nov et al. 2010; Darch and Caruso 2010), there has been no focus on (or even an identification of) the contribution of overclockers. Kloetzer et al. (2016) note the different project roles that can emerge for participants and opportunities for learning, both of which also have been observed in Folding@home. It is of interest that the community of overclockers has not been directly referred to in previous work, and this study (to my knowledge) is the first to explore and acknowledge the contribution of this group to DC in any detail.

Through collaboration and cooperation, teams of overclockers can develop into "communities of practice," which are cohesive groups that possess specialist knowledge and skills that can be transmitted to new members as they learn the "tools of the trade" (Lave and Wenger 1991). Communities of practice have been observed in other online citizen science projects, including in the Foldit Community (Curtis 2015b). Their existence demonstrates that online citizen science can provide an opportunity for groups to develop new skills and knowledge and to make an important contribution to research. Communities of practice also help to motivate sustained participation in these projects because of the opportunities they present for social interaction and learning. Not only does the overclocking community contribute to the generation of new knowledge, it also absorbs some of the financial burden of the project, something that hasn't gone unrecognised by the project team.

Uneven contribution has been observed in many other online citizen science projects. It is especially evident in several Zooniverse projects where small numbers of individuals carry out most of the classification or transcription tasks (Curtis 2015a; Eveleigh et al. 2013; Jennett et al.

2014; Masters et al. 2011; Mugar et al. 2014; Ponciano et al. 2014; Tinati et al. 2014). Indeed, while many thousands of individuals may register, only a few hundred may eventually become active contributors to a project. This has been referred to as a power-law distribution or the 1% rule of the web, where only 1% of Internet users actually contribute content (Cooper 2013). This pattern of contribution has been observed in other types of online communities (Budhathoki and Haythornthwaite 2013; Ciffolilli 2003) and explored in detail by Preece and Schneiderman (2009). While hundreds of millions of people use the Internet, only a small fraction of them move from just reading content to becoming contributors of content. Some contributors move beyond this individual effort and become collaborators and form connected networks with other individuals having a particular focus (e.g., a Wikipedia article or an online game wiki). Of this group of collaborators, an even smaller number of participants may become involved in activities such as helping novices or establishing and enforcing community policies.

Preece and Schneiderman (2009) have described this pattern of participation in their "reader-to leader" framework. This describes the journey that small groups of individuals make from reading content, to contributing content, to collaborating with others, to eventually becoming a "leader" of the community. While the number of "readers" may be great, the number of individuals moving to each successive stage rapidly decreases. This framework also illustrates that users don't always progress from one stage to another, and that movement can occur in both directions between the different levels of participation. While this model is of relevance, I have created a more appropriate model dbased on an analysis of previous research on patterns of participation in online citizen science projects, including these data on Folding@home (**Figure 5**).

From the population of all registered users (the grey zone), a smaller number of participants will become more deeply interested in the project and participate on a regular basis and over a longer period of time (the blue zone). These individuals are more likely to become involved in social aspects of the project and perform other project roles such as managing online forums. This group of active participants may show this level of commitment from the beginning of their involvement in a project, or may emerge from a group of more casual participants (the yellow zone). Such participants, referred to as "dabblers" in some Zooniverse projects, contribute more lightly when they have the time or inclination (Jennett et al. 2014). Conversely, active participants may reduce their level of contribution and move to the group of more transient participants. This is illustrated in the figure as the green "transition zone," which shows that movement can occur between these two groups of participants.

Out of the group of active participants will emerge a number of core participants. These citizen scientists are more likely to interact with each other and with members of the project team. They may work together either cooperatively or collaboratively and mentor new participants. Core participants do not emerge from the group of transient participants or dabblers, because they require an in-depth knowledge of the project and the related tasks, something that is more likely to be acquired during active participation. Such participants are likely to be more motivated by the enjoyment they derive from social interaction and being part of a community. Dedicated communities of overclockers will form the core group of participants in DC projects.

While this model has been based upon available research in online citizen science, it would benefit from further testing and could be made more relevant through the incorporation of new data relating to patterns of participation. Much of the previous work in this area has explored Zooniverse projects, and patterns of participation found within other projects would be of interest.

Conclusions

Overclockers in Folding@home (and most likely in other DC projects) constitute a significant "workforce" and could be considered the unsung heroes of many projects. Not only do they bring their expertise and enthusiasm, they also shoulder a proportion of the financial cost of running protein folding simulations. While previous research in DC has alluded to different types of contribution, the community of overclockers has never been singled out or highlighted. Indeed, it is difficult to find a direct reference to this group in anything that has been previously published about DC projects. Given that DC projects have

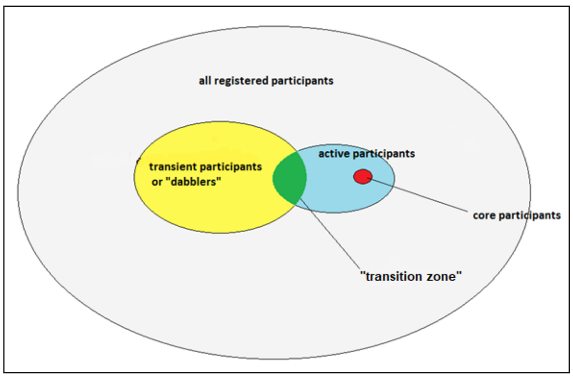

Figure 5: Patterns of participation in online citizen science projects.

been around for more than two decades, and given the number of participants over this time, overclockers have made an invaluable contribution to scientific research.

Identifying and exploring this community was possible through the adoption of a multi-method case study approach. It enables a depth of understanding that lends itself well to the study of citizen science communities of all kinds, and the collection of multiple streams of evidence permits some data triangulation. Further research, particularly research that uses an ethnographic approach, could shed more light on the overclocking community and help to fully uncover the impact that this group of enthusiasts has had on other DC projects.

Additional File

The additional file for this article can be found as follows:

- **Appendix A.** Online Questionnaire. DOI: https://doi.org/10.5334/cstp.109.s1

Notes

[1] As of March 2018.
[2] http://www.kakaostats.net/donors (accessed 27-3-17).
[3] BOINC stands for *Berkeley Open Infrastructure for Network Computing*. BOINC software (or 'middleware') is now used in most distributed computing projects. It is based on the software originally developed for SETI@home.
[4] Data collection was approved by the Open University Human Research Ethics Committee.
[5] Discussion thread relating to health issues and reasons for folding: https://hardforum.com/threads/why-we-dc.759393/.
[6] The Kakaostats site was also used to make this calculation.
[7] EVGA is a hardware and motherboard manufacturer.

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Competing Interests

The author has no competing interests to declare.

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