NETWORK COOPERATION AND INCENTIVES WITHIN ONLINE COMMUNITIES

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ABSTRACT: The aim of this article is to understand the rationale of cooperation at work within online sharing communities. How can the extent of cooperative interactions between anonymous and spatially-dispersed Internet users be explained? We have built a game-theoretic framework to study the exchange of services within a virtual community, such as a peer-to-peer network. It will be shown that the coexistence of contributors and free-riders often yields a stable situation. The optimal incentive mechanisms for stimulating contributions from community members will also be examined.

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Introduction

Since its origins, the Internet has always been perceived as a worldwide collaborative network for information-sharing and has facilitated the emergence of various forms of online gifts and cooperation (Kollock, 1999; Dang-Nguyen and Penard, 2001). Many academic / scholarly communities, non-profit organisations and individual users are now accustomed to transmitting and sharing free informational content or providing advice and assistance free of charge. Increased development of electronic commerce (B2C or B2B) could have jeopardized online cooperation and informational "gifts" via the Internet. Surprisingly however, this did not come to pass, and the well-publicised phenomenon of peer-to-peer file exchange serves as the best illustration of the continued vitality of online cooperation. Peer-to-peer (P2P) is a technology based on the direct exchange of resources from computer to computer at the edges of the Internet. In 2003, the worldwide P2P exchange of audio files was estimated at 150 billion in number and the exchange of movie files at 1 billion[2]. More than 7 million Internet users are simultaneously connected on P2P networks (Kazaa, eMule, …) every day.

Cooperation over the Internet however is widely considered as a puzzling phenomenon: how can the extent of cooperative behaviour both within and beyond online communities be explained, given that Internet users are generally anonymous, remotely-located and too numerous to rely upon mutual trust and reciprocity? What then are the incentives behind cooperating and sharing information content on the Internet?

The aim of this article is to analyse the properties and rationale of online cooperation through a game-theoretic framework. We will focus on sharing communities, e.g. file-sharing communities or discussion forums. The ease of entering and exiting such communities hinders the replication of the same cooperative patterns like in "physical" communities where members are constrained in their movements (switching costs due to location, social pressures, etc.). Within these *offline* communities, long-term reputation and reciprocity are generally strong drivers for stimulating cooperative behaviour (Axelrod, 1982). In contrast, Internet sharing communities appear to be loose-knit and cannot easily self-enforce cooperation via long-term reputation mechanisms.

To explain the vitality of online cooperative behaviour in virtual communities, we propose a model closely tied to the work by Krishnan *et al*. (2004), who constructed a

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[2] Source: IDATE.

content-sharing model within a P2P network where users are heterogeneous with respect to the content they own. These authors showed that both free-riding (consuming without contributing content) and sharing (consuming and contributing) can be observed at the equilibrium point; they highlighted that sharing may occur in the absence of altruism, through motivation by self-interest given that sharing content serves to offload traffic in the P2P network and increase the likelihood of accessing desired content. They also showed that under conditions of symmetric sharing costs, high-value content is shared before lower-value content, with this result being reinforced in a dynamic context where contents are replicated and propagated throughout the network.

Our model differs slightly from that of Krishnan *et al.* (2004). We have considered herein an online community in which peers are given the opportunity to submit requests or queries to other peers (e.g. a request to download a given audio file, a request for assistance or advice). In such communities, contributing involves not only sending requests, but also processing requests from other peers, whereas free-riding would consist of refusing to answer queries from other members. The originality of our model stems both from the heterogeneity in contribution costs (i.e. some peers are more competent or efficient in processing requests) and from the presence of a delay cost when requests are not immediately processed.

Like in Krishnan *et al.* (2004), we show that online cooperation is characterised at the equilibrium point by the coexistence of heavy contributors and free-riders when users exhibit a heterogeneous contribution cost profile. The presence of intense free-riding is not always therefore a sign of cooperation breakdown and can durably persist within sharing communities. However, the level of free-riding is higher than the socially optimal level. We will also consider the impact of external incentives on free-riding behaviour, through examining monetary incentives and priority mechanisms. These external incentives can remedy excess free-riding since online communities generally have no means by which to filter entry or exclude members from services.

The remainder of this paper is organised as follows. The next section provides greater evidence to substantiate cooperative behaviour on the Internet and reviews some of the possible explanations. Section 3 develops a theoretical model of the P2P community. Propositions and implications will be discussed in Section 4, followed by the concluding section.

Section 2: Theory and evidence

Evidence of free-riding in online communities

In a community, individuals always have a common interest and collectively are better off when all members decide to cooperate or coordinate their efforts. Curien *et al.* (2004) distinguish different types of communities: *epistemic communities*, where members produce knowledge like in a community of open source software developers; *communities of practice*, where members exchange expertise or information like in a technical support forum; and lastly *content-sharing communities*, where members directly share resources like in a P2P network. In addition to such a classification, all these communities share one common attribute: their output is a public good, subject to potential *free-riding* or opportunistic behaviour. Each community member is tempted to cheat, i.e. by consuming without contributing, letting the other members incur the cost of providing the public good. Under these conditions, how do members of online communities overcome free-riding and sustain stable cooperation? What are the motivations behind contributing?

These questions may be answered differently depending on the type of online community. Epistemic communities are characterised by strong barriers to entry and exit and by a high contribution cost (requiring rare and specific competences or skills). Since their size is somewhat limited, they can efficiently rely upon more classical cooperation mechanisms, based on bilateral or multilateral reputation. In these communities, members realise that they are repeatedly interacting with the same partners and can endure retaliation in the case of cheating. It does prove rather difficult or costly to escape punishment, since leaving an epistemic community involves losing one's reputation as well as the benefits associated with it. Moreover, the small number of partners enables the community to quickly determine who has "cheated" and to personalise the punishment (e.g. by use of "tit-for-tat" (Axelrod, 1984) or "stick-and-carrot" punishment (Abreu, 1982)). The possibility of "retaliation" constitutes a strong incentive for maintaining cooperation and explains to a large extent the stability of epistemic communities. The relationships between Internet operators, also called ISP's (Internet Service Providers), illustrate this cooperative logic. The operators form a club, in which each member decides with whom it accepts to interconnect at exchange nodes. Cooperation occurs by means of peering agreements, where each ISP agrees to convey all traffic incoming to its network free of charge and generates revenue solely from fees paid by its own subscribers[3]. In many instances, these agreements are not formalised (i.e. not written) and rely upon mutual trust. Open source communities provide other examples of cooperation based on a direct multilateral reputation mechanism. In many open source projects, the number of members is limited (members are co-opted), and each developer has a strong incentive to contribute honestly so as to encourage others to contribute not only to ongoing and future projects, but also to indicate this capability to future employers (Lerner and Tirole, 2002)[4].

The remainder of the article will focus on the other two communities, i.e. practice and sharing communities, in which members exchange advice, expertise, information or other resources. These virtual communities are characterised by weak barriers to entry and exit, a large membership and an affordable contribution cost. In such extensive communities, the multilateral retaliation mechanism cannot be applied easily or becomes less efficient. Some of these communities can encompass up to millions of individuals from anywhere, all of whom agree to share certain resources (information, content, advice, etc.) even though they do not physically know their partners. Since the ease of entering and leaving a community yields, at first glance, a strong incentive to "cheat", the existence and stability of these vast Internet communities give rise to a theoretical puzzle. The communities however seem to manage quite well the sizable presence of free-riding. For example, Adar and Huberman (2000) observed in August 2000 that on the Gnutella (0.6) P2P network, two-thirds of users did not make any contribution at all (namely, by refusing to allow access for their files to be downloaded by peers), whereas the top 1% of users provided 50% of the total content. Similarly, Asvanund *et al*. (2004) found in September 2002 that 42% of Gnutella peers were free-riders. Peers are also less likely to contribute resources to the network as network size increases. Asvanund *et al.* (2004) provided evidence of congestion effects that can offset positive network externalities resulting from a wider P2P community. Peers would have a higher propensity to free-ride as group size rises, thus confirming Olson's intuition (1965).

Similarly, Resnick and Zeckhauser (2002) found that on eBay, the Internet auction leader, 40% of buyers refuse to release an evaluation of their trading partners (whether positive or negative). This attitude may be assimilated to free-riding since evaluation of the trading partner is a public good that helps other buyers within the eBay community in their future transactions, e.g. these evaluations enable buyers to build a reputation for each eBay

[3] This is a "sender keeps all" scheme. The network originating the traffic holds all the money paid by its customers to access other networks (see Bailey, 1997).
[4] See Johnson (2002) regarding the impact of community size on the efficiency of open source projects.

seller (Houser and Wooders, 2006; Friedman and Resnick, 2001). Along the same lines, Dellarocas *et al.* (2004) observed rare coin auctions on eBay and found that 23% of sellers and 33% of buyers did not submit feedback.

In all these examples, free-riding seems to be the common dominant norm, yet apparently does not threaten or undermine the existence and stability of Internet communities. Under these circumstances, why do some members accept to contribute intensively to helping the community function and to providing public goods such as disseminating information?

Motivations for contributing

One reason often forwarded is tied to the origins of the Internet: cooperation is supposedly rooted in the "academic" spirit of the Internet. The essence of academic life is publication (the "publish or perish" motto), in making one's own discoveries available to the whole community of scientists. This tradition of releasing and freely sharing information production has progressively been adopted by non-academic newcomers on the Internet, who seem to have been indoctrinated and converted to the academic spirit of free sharing. The stability of cooperative behaviour amongst Internet communities can thus be analysed as a *stable evolutionary strategy* with the property to resist the influence of alternative strategies, in particular free-riding strategies (Maynard-Smith, 1982).

Altruism can also be a driver for sharing and contributing within a virtual community. Gu and Jarvenpaa (2003) empirically showed, for example, that members of technical support forums are largely motivated by a "warm glow" effect (one of pure utility derived from contributing and helping other members[5]). Back to the eBay context, the feedback provided by buyers may similarly be motivated by a feeling of belonging to a community that promotes courtesy, fairness and truthfulness, as exemplified by the high proportion of positive evaluations (only 1% of non-positive evaluations!)[6]. Dellarocas *et al.* (2004) found that self-interest is an important motivating force behind the strong numbers of positive evaluations. Many traders in fact first send feedback to elicit a reciprocal response (i.e. selfish motivation)[7], yet they also demonstrate some altruistic motivation when eBay members agree to unconditionally evaluate their partner (the "warm glow" effect). Dellarocas *et al.* (2004)

[5] Warm-glow effects have been widely noticed in real communities, in particular through donations (see Andreoni, 1989).
[6] For Gross and Acquisti however (2003), this finding hides a fear of retaliation and some imbalances among eBay "peers". See also Miller, Resnick and Zeckhauser (2005).
[7] They have found that the probability of contributing decreases if the partner has still yet to release his evaluation.

concluded that the motivation behind contributing to eBay's review system is multifaceted (ranging from self-interest and reciprocity to altruism).

Online cooperation can also be explained by the nature of contributions that involve offering informational content. It is often more expensive to protect one's own information or keep it secret than to share it freely. An Internet user needs to undertake a costly effort to avoid participating in the public provision of information. This perspective contrasts with a classical public good setting, where the user only bears a cost if contributing. The relative cost of contributing or not is indeed important in explaining the extent of cooperation within online communities: contributors are generally characterised by incurring a higher personal cost when they refuse to contribute than when they agree. This is the case in open source communities or technical forums where many members find it more worthwhile to make their information available, as this approach fosters technical improvements and innovation.

Cooperation may also be explained by the technical architecture or design of online communities. In many P2P networks for example, each peer (client) is a server/contributor by default. When a peer downloads a file on a PC, this file automatically becomes available for uploading by other peers, except if explicitly forbidden. Hence, being a free-rider (retrieving and hiding the downloaded files) requires certain technical skills and can prove to be time-consuming.

To summarise our discussion thus far, cooperation tends to emerge and persist in large and loose-knit communities composed of anonymous individuals without engaging in repeated bilateral relations, despite high levels of free-riding. In the following section, we will propose a game-theoretic framework to analyse the dynamics of online cooperation more rigorously.

Section 3: A model of peer-to-peer cooperation

This model considers a community of Internet users or peers loosely linked by a common interest, e.g.: a peer-to-peer community exchanging music files (Kazaa), a community of software users exchanging programs and assistance, a thematic community exchanging ideas and opinions. Belonging to a community allows members to send requests or queries to other members, expecting that some will respond. The request could concern a music file, assistance or advice. According to this model, the online community is narrowly defined as an electronic network that allows exchanging requests. An Internet user continues to belong to the community as long as he or she is sending requests.

Technically speaking, the submission of a query or request can be either decentralised or centralised. In the latter case, all requests are routed to a server or coordinator in charge of soliciting the various peers and finding those agreeing to process the request. In a decentralised design, the sender solicits community members directly, either simultaneously or sequentially. The main advantage of a centralised network is the efficiency gained in processing requests, while the main drawback would be vulnerability (should the central server shut down, e.g. Napster). A decentralised network (Kazaa, Morpheus, Gnutella 0.6, etc.) is therefore better suited to large-sized communities and can respond to threats from prosecution, even though it makes much greater demands on community members (Gu and Jarvenpaa, 2003; Asvanund, Clay, Krishnan and Smith, 2003)[8].

We are considering here a decentralised community without detailing the request transmission mechanism. When members are solicited, they can either agree or refuse to process a request. Two types of members can thus emerge in a community: contributors who send requests yet also respond to some; and non-contributors who send requests without processing any requests from other members.

Can the presence of many free-riders destabilise cooperation inside a virtual community? Our model makes it possible to understand how online cooperation can be sustained when a considerable proportion of members never want to contribute to community service provision (by releasing and transmitting contents or files, or by answering requests). Let's now take a closer look at the model assumptions.

Assumptions

We are assuming that members incur a cost when they decide to contribute. This cost can correspond to the efforts and time required to process requests or respond (files, information) to other members of the community[9]. One key assumption in this model is that peers are confronted with different costs. In other words, they are heterogeneously distributed

[8] For example, in recent P2P networks, the contents catalogue is distributed among several peers, who agree to act as local servers. The users log in to one of these "ultra-peers" to submit requests. The ultra-peers then collect the list of contents from all connected peers who accept to share a part of their resources. On the basis of this catalogue, the ultra-peer may either respond to or satisfy the request. Otherwise, the latter transmits the requests to the other ultra-peers within the network. This represents a relatively efficient and secure hybrid solution between full centralisation and full decentralisation, which is assumed to reduce free-riding and improve performance. See Krishnan *et al*. (2003) for a more detailed presentation of P2P architectures, along with their respective advantages and weaknesses.

[9] The decision to contribute is binary. See Curien *et al.* (2004) for a model whereby peers can select the intensity

in their competence or ability to process requests. For example, should the quality of Internet access differ, it is likely that those with broadband access will face lower costs in responding to requests[10]. We would also expect the more educated members of the community to possess higher skill levels (and hence incur lower costs when processing requests).

Let's assume that individual costs are distributed between $[\underline{c},\bar{c}]$ according to a density function *f* and cumulative function *F*. A peer's decision to contribute or free-ride will directly depend on the cost incurred. The peer thus faces the following trade-off: free-riding allows saving on the cost of participation, yet it degrades the quality of community services by increasing the likelihood of congestion during request processing. Contributing can prove to be a better strategy if the participation cost is more than offset by the increase in quality of services provided by the community. By agreeing to process requests, a peer knows that he or she is contributing to reducing congestion and thereby enhancing the probability of a rapid processing of his/her own requests.

If all members whose cost is less than $\hat{c} \in [\underline{c},\bar{c}]$ agree to contribute, the proportion of contributors will then be: $F(\hat{c}) = \int_{\underline{c}}^{\hat{c}} f(c)dc = \int_{\underline{c}}^{\hat{c}} dF(c)$).

Let's assume that peers are all sending the same number of requests and that this number has been normalised to 1 for the sake of convenience. Moreover, let *N* be the volume of requests simultaneously sent per period. We can interpret *N* as the intensity of community activity or the network capacity to handle request transmissions. *N* is obviously positively correlated with the size of the community (i.e. the number of peers).

Let $\alpha(\hat{c},N)$ denote the probability that a request is being instantaneously processed. We now make the following assumptions on $\alpha(\hat{c},N)$: i) $\alpha_{\hat{c}}(\hat{c},N) > 0$, ii) $\alpha_{\hat{c}\hat{c}}(\hat{c},N) < 0$, iii) $\alpha_N(\hat{c},N) < 0$, iv) $\alpha_{NN}(\hat{c},N) > 0$, and v) $\alpha_{\hat{c}N}(\hat{c},N) < 0$. The probability of request processing is an increasing and concave function of $\hat{c}$. As the proportion of contributors inside the community grows, request processing becomes faster. But the positive effect of one additional contributor tends to diminish as the number of contributors and volume of requests (or community size) rise. Moreover, $\alpha(\hat{c},N)$ is decreasing and convex in *N*: a larger community contributes to degrading the quality of request processing by reinforcing the risk of

of their contribution.

[10] Processing the requests does imply a reduction of resources for other activities, in particular a reduction of the contributor's bandwidth available for other applications. Feldman, Lai, Chuang and Stoica (2003a) underscored the actual disincentive effects due to the symmetric treatment of uploading and downloading within P2P networks due to the download latency being dominated by the sender's outgoing bandwidth; the sender's computer link is often taxed by providing service to peers at the expense of fulfilling his or her own requests.

congestion. When the number of peers increases along with the request volume, contributors are more heavily solicited and cannot satisfy all requests; consequently, processing is more likely to be delayed. Let's also assume that $\alpha(\underline{c}, N)$ =0 (i.e. in the absence of contribution, the online community is fully congested).

We denote *u* as the utility for a member to send a request and immediately obtain an answer or assistance. Being confronted with a delay in request processing induces a disutility for the sender. The utility of a request processed *t* periods after its transmission would be $\delta^t u$, where δ is the discount factor (common to all community members).

When a request fails to be processed during the initial period, it gets resubmitted until an answer is received. Sending a request thus yields an expected utility *G*, defined by:

$$G = \alpha(\hat{c}, N)u + (1 - \alpha(\hat{c}, N))\delta G$$

After rearrangement, we obtain:

$$G = \frac{\alpha(\hat{c}, N)u}{1 - \delta + \delta\alpha(\hat{c}, N)}$$

where G represents the expected benefit of belonging to a community (and of sending a volume of requests normalised to one) with a proportion $F(\hat{c})$ of actively-contributing peers. *G* is increasing and concave in $\hat{c}$ (i.e. with the number of contributors)[11]. This benefit also rises with the peer's discount factor (future preference). In the following proposition, we have characterised peer equilibrium strategies within this virtual community.

PROPOSITION 1: EQUILIBRIUM CONDITIONS FOR ONLINE COOPERATION

If $\underline{c} > \dfrac{(1-\delta)\alpha_{\hat{c}}(\underline{c}, N)u}{(1-\delta+\delta\alpha(\underline{c}, N))^2}$ *, then all peers refuse to cooperate (no community)*

If $\bar{c} < \dfrac{(1-\delta)\alpha_{\hat{c}}(\bar{c}, N)u}{(1-\delta+\delta\alpha(\bar{c}, N))^2}$ *, then all peers contribute (no free-riding)*

Otherwise, $\hat{c} \in [\underline{c}, \bar{c}]$ *exists, as defined by:* $\hat{c} = \dfrac{(1-\delta)\alpha_{\hat{c}}(\hat{c}, N)u}{(1-\delta+\delta\alpha(\hat{c}, N))^2}$*, such that a proportion F(*$\hat{c}$*) of contributors and a proportion (1-F(*$\hat{c}$*)) of free-riders coexist within the same community.*

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[11] We have: $G_{\hat{c}} = \dfrac{(1-\delta)\alpha_{\hat{c}}u}{(1-\delta+\delta\alpha)^2}$>0 and: $G_{\hat{c}\hat{c}} = \dfrac{(1-\delta)\left[\alpha_{\hat{c}\hat{c}}(1-\delta+\delta\alpha)u - 2\delta(\alpha_{\hat{c}})^2\right]}{(1-\delta+\delta\alpha)^3}$<0.

Proof: A peer will agree to contribute if the cost in efforts is less than the marginal gain. If $\underline{c} > \frac{(1-\delta)\alpha_{\hat{c}}(\underline{c},N)u}{(1-\delta+\delta\alpha(\underline{c},N))^2}$ or $\underline{c} > \frac{(1-\delta)\alpha_{\hat{c}}(\underline{c},N)u}{(1-\delta)^2}$ (since $\alpha(\underline{c},N)=0$), then the most competent peer has no incentive to contribute and, consequently, this would also be the case for all other less competent peers.

Let's now look at $\underline{c} \leq \frac{(1-\delta)\alpha_{\hat{c}}(\underline{c},N)u}{(1-\delta+\delta\alpha)^2}$. At least one peer agreeing to contribute can then be found. Consider that a peer exists whose cost $\hat{c}$ makes him/her perfectly indifferent to accept or refuse processing requests, given that all of the more competent peers are contributors. For this marginal peer, the additional gain from contributing $\frac{(1-\delta)\alpha_{\hat{c}}(\hat{c},N)u}{(1-\delta+\delta\alpha(\hat{c},N))^2}$ should be perfectly equal to the additional cost ($\hat{c}$). It can then be recursively shown that any peer whose cost is less than $\hat{c}$ also has an incentive to contribute (knowing that a refusal to contribute will encourage all peers with a higher cost to refuse as well). However, if $\bar{c} < \frac{(1-\delta)\alpha_{\hat{c}}(\bar{c},N)u}{(1-\delta+\delta\alpha(\bar{c},N))^2}$, even less competent peers are seeking to contribute, and there is no free-riding inside the community. ■

Proposition 1 underscores that inside the community, contributors are always the more competent or efficient peers. This result is similar to that derived by Krishnan *et al.* (2004), who showed that contributors possess the highest value content. Hence, should members be widely heterogeneous (i.e. $\underline{c}$ sufficiently low and $\bar{c}$ sufficiently high), the community will be characterised by partial cooperation. The more competent members (those whose cost lies below $\hat{c}$) will agree to contribute, whereas the others are mere consumers of community services. The presence of free-riders therefore is not incompatible with a cooperative community. It may be in the interest of highly-skilled members to continue contributing and maintaining the community active because they are aware that they would be indirectly penalised if they were to stop processing peer requests (which would mean more congestion for their own requests). If community members show a strong preference for the present ($\delta < 1 - \frac{\alpha_{\hat{c}}(\underline{c},N)u}{\underline{c}}$) however, no one will then agree to contribute: in this case, no sustainable cooperation will emerge from this community. Online cooperation proves feasible only if members are sufficiently patient (high preference for the future).

The impact of community size

The worldwide expansion of the Internet has heavily affected the operations and activities of online communities. Most have welcomed newcomers from throughout the world and have dramatically grown (some Internet communities can unite several million users). Does the boom in Internet communities represent a threat or opportunity for them? It can be expected that new members are more likely to be free-riders due to their lack of competence or expertise. But it is also possible that the arrival of new members may incite some current free-riding members to contribute and counterbalance the negative effect of the increase in request activity generated by newcomers. It is thus debatable whether a larger community size destabilises or reinforces cooperation.

By differentiating $\hat{c} = \frac{(1-\delta)\alpha_{\hat{c}}(\hat{c},N)u}{(1-\delta+\delta\alpha(\hat{c},N))^2}$, we obtain:

$$\frac{d\hat{c}}{dN} = \frac{-2(1-\delta+\delta\alpha)\delta\hat{c}\alpha_N + (1-\delta)\alpha_{\hat{c}N}u}{(1-\delta+\delta\alpha)^2 + 2(1-\delta+\delta\alpha)\delta\hat{c}\alpha_{\hat{c}} - (1-\delta)\alpha_{\hat{c}\hat{c}}u}$$

The sign of the denominator is always positive, but the sign of the numerator remains undetermined. A larger community can create new incentives to contribute and may increase the proportion of contributors if $2(1-\delta+\delta\alpha)\delta\hat{c}\alpha_N < (1-\delta)\alpha_{\hat{c}N}u$. This condition is likely to be satisfied if the risk of congestion is high (i.e. α_N high in absolute value) or if members have a strong preference for the future (δ high[12]).

Proposition 2: *Enlargement of the online community may reinforce cooperation if peers are sufficiently patient.*

An increase in community size (or in its activity) does not systematically threaten its stability. As the risk of congestion becomes higher, some free-riders may realise that their efforts could be determinant to maintaining cooperation and may decide to join the club of contributors.

[12] For δ=1, the condition becomes $2\alpha\hat{c}\alpha_N < 0$, which is always true.

The optimal level of cooperation

Does decentralised online cooperation lead to an optimal level of contribution and request processing? Is the number of contributors too few or too many? To address this question, we must identify the level of cooperation that maximises the collective surplus of the online community. This optimal level $\tilde{c}$ is given by:

$$Max_{\{\tilde{c}\}}\left(\frac{\alpha(\tilde{c},N)u}{1-\delta+\alpha(\tilde{c},N)\delta}\int_{\underline{c}}^{\bar{c}} f(c)dc-\int_{\underline{c}}^{\tilde{c}} cf(c)dc\right)$$

It has been noted that costs are only borne by contributors $[\underline{c},\tilde{c}]$, whereas benefits $G(\tilde{c})$ are equally shared among all peers $[\underline{c},\bar{c}]$. Thus, $\tilde{c}$ can be defined as:

$$\tilde{c}f(\tilde{c})=\frac{(1-\delta)\alpha_{\tilde{c}}(\tilde{c},N)u}{(1-\delta+\delta\alpha_{\tilde{c}}(\tilde{c},N))^2}\int_{\underline{c}}^{\bar{c}} f(c)dc$$

The right-hand side stands for the marginal collective benefit if peers displaying a cost $\tilde{c}$ decide to actively contribute to the activity, and the left-hand side expresses the collective cost incurred by the peers displaying a cost $\tilde{c}$.

PROPOSITION 3: *Decentralised online cooperation always induces an excess of free-riding when the community is heterogeneous.*

Proof: Since $\frac{f(\tilde{c})}{\int_{\underline{c}}^{\bar{c}} f(c)dc}<1$, then $\tilde{c}\frac{f(\tilde{c})}{\int_{\underline{c}}^{\bar{c}} f(c)dc}=\frac{(1-\delta)\alpha_{\tilde{c}}(\tilde{c},N)u}{(1-\delta+\delta\alpha_{\tilde{c}}(\tilde{c},N))^2}<\tilde{c}$ (i.e. $G_c(\tilde{c})<\tilde{c}$). Since $G_c(\hat{c})=\hat{c}$ and $G_{cc}<0$, then $\tilde{c}>\hat{c}$. ■

Note that optimal online cooperation does not imply full participation (except if $\bar{c}\frac{f(\bar{c})}{\int_{\underline{c}}^{\bar{c}} f(c)dc}<\frac{(1-\delta)\alpha_{\tilde{c}}(\bar{c},N)u}{(1-\delta+\delta\alpha_{\tilde{c}}(\bar{c},N))^2}$), but merely the coexistence of contributors and free-riders. It may be a suboptimal approach to force all peers to contribute, especially the less competent ones (since the quality of their contribution is low).

The stakes for an online community are to maintain and, if possible strengthen, cooperation within a context of membership growth where screening of newcomers is difficult to implement. In the following section, we will consider various incentive designs that have already been experimented or debated in online communities.

Section 4: How to stimulate online cooperation?

The recent interdisciplinary literature on the topic examines the means for reducing free-riding within P2P networks and online communities. What sort of incentives should members be receiving in order to furnish resources, content or effort? Some authors have proposed micro-payment mechanisms (Golle *et al.*, 2001), reputation systems (Lai *et al.*, 2003), admission control systems (Kung and Wu, 2003) or priority systems (Krishnan *et al.*, 2004). These systems however generally rely on centralised administrations and are not easily implemented in most online communities (based on decentralised architecture). Nevertheless, it is worthwhile to try to understand how such systems could improve cooperation in our decentralised community setting.

We will examine two cooperation-fostering mechanisms: the introduction of monetary incentives, and the use of priorities in processing requests. Can these two mechanisms improve the performance of the community, enhance the matching and routing of requests and reduce the level of free-riding?

Monetary incentives

Let's start by assuming that every non-contributor must pay p to participate in the community and that the collected monetary sum is equally shared amongst contributors. Each contributor then receives $\left(\frac{1-F(\hat{c})}{F(\hat{c})}\right)p$, where $F(\hat{c})$ is the contributor's proportion.

Monetary incentives alter the trade-off between free-riding and cooperating. The level of cooperation is now determined by the following condition:

$$\hat{c}_p = \frac{(1-\delta)\alpha_{\hat{c}}(\hat{c}_p, N)u}{(1-\delta+\delta\alpha(\hat{c}_p, N))^2} + \left(\frac{1-F(\hat{c}_p)}{F(\hat{c}_p)}\right)p$$

where $\hat{c}_p$ is the peer who is indifferent between contributing and free-riding.

A higher payment p leads to a greater proportion of contributors in the online community. However, monetary incentives yield decreasing returns. Indeed, as p increases, the proportion of contributors rises and tends to 100%, thereby reducing the share claimed by each contributor.

A fee level $\bar{p}$ can therefore be found such that $\hat{c}_{\bar{p}} = \bar{c}$. Fees rising above $\bar{p}$ would create no additional incentives inside the community[13].

It is important to bear in mind that most online communities are decentralised and cannot technically or practically control access and exclude members. Membership fees are thus difficult to enforce. Fees must be voluntary in an anonymous community. A centralised community would obviously be operated differently, with sponsorship and management by either a non-profit or for-profit organisation (e.g. eBay, Amazon, Yahoo).

At this point, let's consider the incentives of non-contributors to voluntarily remunerate contributors. The expected benefits of this voluntary transfer outweigh costs when:

$$\frac{\alpha(\hat{c}_p, N)u}{1-\delta+\delta\alpha(\hat{c}_p, N)} - \frac{\alpha(\hat{c}_0, N)u}{1-\delta+\delta\alpha(\hat{c}_0, N)} > p$$

PROPOSITION 4: *If* $\hat{c}_0 \geq 1 \Big/ \dfrac{d\hat{c}_p}{dp}$*, then a voluntary payment mechanism may be feasible even in a decentralised community.*

Proof: This problem can be reformulated as follows. The net benefit for a free-rider is defined by:

$$B(p) = \frac{\alpha(\hat{c}_p, N)u}{1-\delta+\delta\alpha(\hat{c}_p, N)} - p$$

By differentiating with respect to *p*, we obtain:

$$\frac{\partial B(p)}{\partial p} = \left(\frac{(1-\delta)\alpha_{\hat{c}}(\hat{c}_p, N)u}{\left(1-\delta+\delta\alpha(\hat{c}_p, N)\right)^2}\right)\frac{d\hat{c}_p}{dp} - 1$$

Since $\hat{c}_p = \dfrac{(1-\delta)\alpha_{\hat{c}}(\hat{c}_p, N)u}{\left(1-\delta+\delta\alpha(\hat{c}_p, N)\right)^2} + \left(\dfrac{1-F(\hat{c}_p)}{F(\hat{c}_p)}\right)p$, then:

$$\frac{\partial B(p)}{\partial p} = \frac{d\hat{c}_p}{dp}\left(\hat{c}_p - \frac{1-F(\hat{c}_p)}{F(\hat{c}_p)}p\right) - 1.$$

Then

[13] In other words, the differential in the marginal benefits of contributing with and without monetary incentives decreases and tends to zero as *p* becomes larger.

$$\left.\frac{\partial B(p)}{\partial p}\right|_{p=0} = \hat{c}_0 \frac{d\hat{c}_p}{dp} - 1$$

If $\hat{c}_0 < 1 \Big/ \frac{d\hat{c}_p}{dp}$, then $\left.\frac{\partial B(p)}{\partial p}\right|_{p=0} < 0$ and non-contributors will refuse to voluntarily pay for their request submission. ■

Voluntary payment is more a likely scenario if the proportion of free-riders is sufficiently low (i.e. if 1-$F(\hat{c}_0)$ is low or, equivalently, if $\hat{c}_0$ is high); however, in the event of too many free-riders, the net benefit from monetary incentives does not counterbalance costs.

Note that this proposition is useful in helping understand why many communities are based on free interactions, without monetary compensation. As an example, the community of Internet carriers is characterised by a predominance of peering agreements, where each carrier holds all revenue from its customers and exchanges traffic with peers without any monetary compensation.

A priority system

Another mechanism for promoting cooperation consists of assigning priority to contributor requests as a means of encouraging participation. Such a mechanism has been examined by Krishnan *et al.* (2004). According to these authors, differentiating between the quality of services provided to contributors and non-contributors could improve P2P network performance and is easily implemented even within a decentralised environment. Kazaa developed a priority-like system in which depending on the past behaviour of the peer, requests are processed either as a priority or delayed. Each peer is "scored" relative to the number of files he/she is currently offering to other peers and the number of files (requests) he/she has downloaded.

Let $q\alpha$ denote the probability of being served when the peer is a contributor (q > 1), and α the probability of obtaining a response when a free-rider. We are implicitly assuming here that peers are able to distinguish requests sent by a contributor from those sent by a free-rider. The expected utility of a request sent by a contributor in an online community can then be defined by:

$$G = q\alpha(\hat{c}, N)u + (1 - q\alpha(\hat{c}, N))\delta G$$

which means that for a contributor, the expected utility would be:

$$G^{c}=\frac{q\alpha(\hat{c},N)u}{1-\delta+\delta q\alpha(\hat{c},N)}$$

whereas for the non-contributor, it is: $G^{nc}=\frac{\alpha(\hat{c},N)u}{1-\delta+\delta\alpha(\hat{c},N)}$.

The marginal contributor is now determined as:

$$\hat{c}_{q}=\frac{(1-\delta)q\alpha_{\hat{c}}u}{(1-\delta+\delta q\alpha)^{2}}+\left(\frac{q\alpha u}{(1-\delta+\delta q\alpha)}-\frac{\alpha u}{(1-\delta+\delta\alpha)}\right).$$

The first term on the right-hand side corresponds to the marginal benefit of decreasing congestion and the second term to the benefit gained from a priority assignment.

The equilibrium level of contribution is higher with a priority system, since the incentives to contribute are stronger: direct incentives through the priority label, and indirect incentives through congestion reduction. We can observe that $\hat{c}_q$ is an increasing function in q (which measures the extent of priority).

In reality however, this system may only be of limited efficiency if free-riders are easily able to modify their profile and assume the appearance of a contributor. A network like Kazaa has faced this problem, whereby some users have managed to replace their free-rider profile or score by a contributor's profile.

Taxation as a means of destabilising online communities

The taxation of uploaded flows on the Internet is strongly supported by music companies like Universal, which argue that piracy and P2P networks may be responsible for the drop in recording sales. Several empirical studies have attempted to measure the impact of P2P on music sales. Most have concluded the existence of a significant negative effect, yet this would only partially explain the decline in CD sales over the past few years (Peitz and Waelbrock, 2004; Molteni and Ordanini, 2003; Boorstin, 2004; Hui and Png, 2003; Leibowitz, 2003; Oberholzer and Strumpf, 2004). Nevertheless, music companies view taxation as a means of destabilising P2P communities by making active contribution more costly. A tax would indeed penalise those who agree to make their files downloadable. Our framework enables understanding the rationale behind this taxation scheme for recording companies. The level of cooperation is defined by $\hat{c}_t$, where t stands for the tax applied to contributors:

$$\hat{c}_t + t = \frac{(1-\delta)\alpha_{\hat{c}}(\hat{c}_t, N)u}{(1-\delta+\delta\alpha(\hat{c}_t, N))^2}$$

We can observe that the threshold level of participation is decreasing with respect to tax *t*. If the goal of the music companies is to fully deter online cooperation on P2P networks, they should plead for a minimum tax $\underline{t}$ such that: $\underline{c} + \underline{t} > \frac{(1-\delta)\alpha_{\hat{c}}(\underline{c}, N)u}{(1-\delta)^2}$. With a sufficiently high tax, all community members will refuse to contribute or release content, files, information, etc.

Conclusion

This article has offered a survey of the recent economic literature on P2P systems, as well as a theoretical framework that has provided insight into issues previously discussed in the literature. While many authors stress the point that the reasons why communities persist is a puzzling phenomenon, given the considerable amount of free-riding permeating them, our premise is that a selfish attitude is perfectly consistent with cooperation because such communities contain heavy contributors. The high level of free-riding is explained in our model by the heterogeneity among community members. The main results obtained show that monetary incentives may not be the appropriate strategy for reducing free-riding within these P2P networks, while prioritisation in some cases may be better suited. Integrating the user's self-interest to cooperate in the design of computer networks thus becomes crucial. In Internet communities, free-riding problems can be more readily tackled by a technical response than in real communities (Schneidman and Parkes, 2003).

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