Current Biology Vol 16 No 22
R946

Essay

Digital cows grazing on digital grounds

Thomas Pfeiffer and Martin A. Nowak

Picture a pasture open to all (…) As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, more or less consciously, he asks, "What is the utility to me of adding one more animal to the herd?" This utility has one negative and one positive component. 1) The positive component is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of the additional animal, the positive utility is nearly +1. 2) The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of −1. Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to the herd. And another; and another …

With this picture of herdsmen sharing a pasture, Garrett Hardin illustrates in his influential paper *The Tragedy of the Commons* [1] the vulnerability of common goods towards overexploitation. Whenever users have free and uncontrolled access to exploit a common resource, their individual interests may lead to its overexploitation, although this is of disadvantage for the entire community of resource users. In other words, the selfish interests of the individuals prevent a more productive resource use that would be beneficial for everyone. A similar situation arises for resources that require maintenance. Free-riders who exploit a resource without contributing to its maintenance are better off than individuals who carry the maintenance costs, even if the resource eventually decays.

Hardin [1] points to privatization and governmental control as potential ways of avoiding the tragedy of the commons, mainly focusing on those tragedies that emerge because of the growth of the human population and its impact on the environment. Some more recent developments on these issues have been captured in previous essays in *Current Biology* [2,3]. But within the 40 years that passed after Hardin published his paper, the internet emerged — and with it an entire world of novel common goods, novel tragedies and novel, unexpected ways to avoid them.

Common goods in the internet

Modern communication networks such as the internet allow a large number of often anonymous individuals to store and exchange large amounts of information. Thereby they generate a potential for novel common goods consisting of publicly accessible information and/or infrastructure to process it. Excellent examples for such common goods are peer-to-peer networks such as Gnutella, Napster or Freenet [4]. Peer-to-peer networks allow a large number of anonymous users to share files, bandwidth and computing power. Users can contribute to the common good, for example by sharing their files, and can exploit the common good, for example by downloading files. Both processes are usually uncoupled, giving free-riders the chance to exploit the network without contributing. As a consequence, peer-to-peer networks face a similar problem to Hardin's pasture: studies indicate that there is a high degree of free-riding on Gnutella, leading to a decline of network performance [5,6].

Besides peer-to-peer networks, there are numerous other common goods on the internet. Software projects such as GNU (www.gnu.org) provide valuable open-source software; companies like Craigslist (www.craigslist.org) and Amazon (www.amazon.com) provide public space for adverts and product reviews; and eBay (www.ebay.com) provides a public platform for online auctions and trading. Sometimes these public goods serve a purpose for the institutions that host them. For example, book reviews from Amazon's clients may increase the sales and may make Amazon more attractive; and eBay directly benefits from trading activities on its platform. But whether hosted by a profit or non-profit organization, digital common goods are often generated and exploited by a large number of typically anonymous users, and even if hosts can exclude users, it is often not in their interest.

The digital common goods therefore face potential problems with cheating and free-riding. Trading platforms, for example, cannot take off if they are prone to cheating. Providing space for adverts or product reviews invites inadequate, illegal or irrelevant contributions, and creating free software seems like a hopeless act of altruism, considering the presence of commercial companies that can pay high salaries to their software writers. In order to protect these digital common goods, a number of mechanisms have been established. These mechanisms go often far beyond those suggested by Hardin (privatization or access control by the host); rather than relying on centralized control, they are based on self-organized interactions between users.

GNU and GPL

One of the most astonishing solutions to the problem of protecting digital common goods emerged with free software projects such as GNU (www.gnu.org). Free software projects allow the users to copy, modify and redistribute their software. The success of Linux/GNU operating systems shows that free software projects can generate public goods of tremendous value. Free software differs in an important aspect from Hardin's pasture. Because making an additional copy of the existing software comes at almost no cost, digital pastures do not suffer from digital cows grazing on it. But free software projects are still vulnerable to exploitation: competitors, such as commercial software producers, may in principle gain a competitive advantage over free software projects by using and modifying free software and commercializing the resulting products.

In order to prevent this, GNU distributes its software under the terms of the GNU General Public License (GPL) [7,8]. Compared with licenses associated with proprietary software, this license grants excessive rights: the user can run the software, study and modify it, and redistribute the original as well as modified versions. But in addition, GPL requires that derived software has to be distributed under GPL, too. This condition not only limits the degree to which derived software can be exploited commercially: by enforcing that work based on free software is distributed as free software, it promotes the growth of free software. In other words, GPL ensures that digital cows grazing on digital grounds fertilize the growth of digital grass.

Craigslist and Amazon

Craigslist (www.craigslist.org) is a small company with only a handful of employees and a distinctive non-commercial profile, which hosts one of the most popular web pages on the Internet. Essentially, it provides users space to publish advertisements in different categories ranging from job adverts to personal postings. With very few exceptions this is done free of charge, and reading the advert is free of charge, too. With over 10 million adverts published per month, the public space offered by Craigslist is another excellent example of a flowering digital pasture.

But by providing public space free of charge, Craigslist is vulnerable to posting offending, illegal or irrelevant contents. By posting commercial spam, free-riders may even gain direct financial benefits. What is Craigslist doing to avoid this? Almost nothing — it allows its users to take care of that issue. At Craigslist, all users can flag adverts that they consider to be offending, illegal or just irrelevant. If a couple of users flag the same advert, it will be removed. In order to avoid excessive flagging, Craigslist makes flagging time-consuming; and having an interest to keep their favorite categories clean, users invest a little time in 'policing' the site.

The internet bookseller Amazon (www.amazon.com) offers a common good quite similar to the one offered by Craigslist. It allows clients to publish product reviews. Although these reviews are not necessarily positive, and thereby do not necessarily facilitate the sale of a particular product, they certainly make Amazon more attractive. But by offering public space, Amazon runs into the same problems as Craigslist. Some reviews can just be inappropriate. In order to avoid this, Amazon not only allow its clients to write reviews — it also allows them to review reviews, which in turn allows users to identify the most relevant ones.

eBay and its reputation system

eBay (www.ebay.com), with an annual revenue of 4.5 billion US dollars in 2005 making it one of the most successful internet companies, provides a platform for online auctions and trading. Because the presence of a large number of users is of advantage for the functioning of auctions, eBay has an interest not to exclude any users. On the other hand, trading between anonymous users is prone to cheating. Sellers may cheat by not shipping their merchandise after receiving the payment, while buyers may try to keep their items while canceling their payment, using, for example, a credit card chargeback. Legal actions against such cheating are possible but often associated with substantial costs — increasing the cheater's chances to go unpunished.

In order to reduce fraudulent transactions on its platform, eBay uses a reputation system that allows buyers and sellers to evaluate their transactions [9]. The evaluations are published and therefore allow users to avoid transactions with parties of questionable reputation. Experiments on eBay show that a good reputation can translate into monetary value. Sellers with a good and long-lasting reputation can make better deals than their competitors with bad or without any reputation [10]. Although eBay's reputation system is far from perfect — for example, cheaters can change their identity, and the reputation system is prone to retaliation of bad ratings — it is a good example of how reputation can help establish a large degree of cooperation within a community.

Reputation and evolutionary game theory

The success of self-organized mechanisms, such as eBay's reputation system, for the protection of common goods in the internet is paralleled by research on reciprocal altruism in evolutionary game theory. In evolutionary biology, self-organized mechanisms for the evolution and maintenance of cooperation are of specific importance, because for most organisms, the ability to file a complaint against a cheater simply does not exist. eBay's reputation system, for example, resembles mechanisms of 'indirect reciprocity' [11–16], while Craigslist's flagging system resembles 'policing' [17–19] and 'altruistic punishment' [20–22].

Within the framework of reciprocal altruism, cooperative, altruistic actions can be advantageous, despite their costs, if they increase the future prospects of benefiting from altruistic actions of other individuals [23]. In direct reciprocity, individuals reciprocate previous cooperative interactions with their present interaction partner. In Axelrod's famous computer tournaments between various strategies in a direct reciprocity setting, a surprisingly simple strategy called Tit-For-Tat emerged as the champion [24]. Tit-For-Tat starts with cooperation, and then just repeats its opponent's last move. The success of Tit-For-Tat relies on its ability to establish cooperation without being exploited too much by cheaters. Further studies identified strategies such as Generous Tit-For-Tat and Win-Stay Lose-Shift as being even more successful under a wide range of conditions [25,26]. But irrespective of what strategy is being played, direct reciprocity depends on the crucial condition that there are repeated interactions between the same two individuals — a condition that does not necessarily hold in biological populations, and in particular not for interactions between anonymous users in the internet.

But besides the rules of direct reciprocity such as 'be nice to those that are nice to you', mechanisms of indirect reciprocity have been proposed, following the directive to 'be nice to those that are nice to others'. In indirect reciprocity, individuals use information of previous encounters of their present partners with different individuals. One of the first, and again one of the simplest, strategies within this framework is image scoring, a strategy that follows the above directive almost literally [27]. More elaborate strategies such as standing can cope with the problem of distinguishing between unjustified and justified defection, the latter being defection towards an individual with a 'bad' history [11–14]. In an amazing study that appeared recently, Ohtsuki and Iwasa [16] analyzed 4096 strategies within the framework of indirect reciprocity and identified eight that perform best under a wide range of conditions. These 'leading eight' strategies illustrate that indirect reciprocity can be achieved with several similarly good reputation systems that follow different rules.

A mechanism similar to indirect reciprocity is altruistic punishment [21,22]. Here, the rule is 'to punish those who are not nice to others', even if it comes at costs, not only for the punished, but also for the punishing individual. Experiments have shown that altruistic punishment may be of high importance for the maintenance of common goods in human societies [20,28,29].

An important property of interactions on digital grounds is

Box 1

From reputation to climate protection — experiments on human behavior in public goods games.

In experimental settings of public goods games [20,36], players typically interact within small groups, say, with four members. They receive an amount of money and simultaneously decide whether to keep it or invest it into a group project. The experimenter then increases (say, doubles) the money invested into the group project. The return is shared equally between all players of the group.

For a player who tries to maximize his individual payoff, it is the best choice in this game to keep the money and not to invest (see Table 1). This is because each dollar a player invests is first doubled, but then shared among all four players, resulting in a direct return of only 50% of the investment. Making an investment is beneficial for the group but does not maximize the individual payoff, as is typical for a tragedy of the commons. Thus, if played repeatedly between anonymous players, the investments decline rapidly. Initially, most players start somewhat irrationally with a high investment. But soon they experience that they are exploited by free-riders, and thus stop investing [20,36].

This behavior changes if rounds of the public goods game are alternated with rounds of an indirect reciprocity game. In this game, individuals can reward other individuals by, for example, spending a dollar that is transformed into a reward of three dollars for the receiver. Because players only reward individuals with a good reputation it pays to invest in the public goods game. Making investments into the public good translates into a good reputation, which in turn translates into a higher chance of being rewarded in the indirect reciprocity game [36].

A recent study [34] on reputation and climate protection goes even a step further: again, rounds of a public goods game were alternated with an indirect reciprocity game. But the return from the public goods game was not given back to the group. Rather, it was invested into a climate fund, which was used to pay for an advert about the impact of human-induced CO_2 emissions on the Earth's climate. Although the players did not directly benefit from the climate fund, they maintained a high level of investment. By investing into the climate game, players could build up a good reputation, which in turn increased the chances of being rewarded [34,35].

Table 1. Example payoffs in a typical public goods game.

Player	**Amount invested**	**Amount kept**	**Yield from the public good game**	**Total payoff**	**Player**	**Amount invested**	**Amount kept**	**Yield from the public good game**	**Total payoff**
A	1	0	2	2	A	0	1	1.5	2.5
B	1	0	2	2	B	1	0	1.5	1.5
C	1	0	2	2	C	1	0	1.5	1.5
D	1	0	2	2	D	1	0	1.5	1.5
Total	**4**		**8**	**8**	**Total**	**3**		**6**	**7**

The group consists of four players. Each player has one dollar, which can be kept or invested. The total investment of the group is doubled, and then shared equally among all group members. If all players invest (left part of the table), the total investment is $4. The yield from the investment is $8, resulting in a payoff of $2 per player. By keeping rather than investing the money, a player can increase its own payoff at the cost of the others (right part of the table): If only three players invest, the return from the group investment is only $6, or $1.5 per group member. But player A, who kept his dollar now has a total payoff of $2.5.

their voluntary character. Typically, we do not rely on the digital common goods described above. We can choose to use them, but if the risk of being cheated becomes too high, we can choose to not participate at all. Such volunteering has been shown to stabilize cooperation in public goods games [30]. Loners that choose not to participate turn a game where cooperative behavior is always out-competed by cheaters into a rock–scissors–paper game. Cooperative behavior is still out-competed by cheating. Once cheating is the prevailing strategy, however, it is more advantageous not to participate in the game. In a population of loners, in turn, cooperative behavior may spread. These cycles of rise, fall and re-establishment of cooperation resemble the dynamics of peer-to-peer networks that first become popular, then suffer from overexploitation, and finally lose their users to other peer-to-peer networks.

It remains to be seen how much of the findings from evolutionary game theory can be incorporated into the protection of common goods in the internet. But the success of reputation systems even less sophisticated than the ‘leading eight’ is a promising beginning. A common criticism on the more complex strategies of indirect reciprocity is that they depend on reliable information on the behavior of others and require substantial cognitive capabilities in order to evaluate what is ‘good’ and what is ‘bad’. Experiments suggest that even humans tend to use cheaper but less sophisticated strategies such as ‘image scoring’ [31,32].

Presumably even users of eBay’s reputation system tend to use only the rating, but not the stories behind it, although they are available. But in principle it is easily possible to keep track of interactions on common goods in the internet and to handle more complex evaluation schemes. This strength can be expected to favor the development of more powerful mechanisms for the protection of digital common goods. Currently, complex reputation systems are established, for example, for peer-to-peer networks [33]. And maybe the novel mechanisms that help to maintain common goods in the internet may turn out to be suitable to solve the old tragedies addressed by Hardin [1]. Recent experiments on indirect reciprocity (Box 1) between humans in the context of climate control point in that direction [34,35].

Acknowledgments
We would like to thank C.T. Bergstrom, B. Kerr, J. West, and F. Taddei for inspiring discussions. Articles from Wikipedia (another flowering digital resource) turned out to be very valuable for this essay. Support from the John Templeton Foundation and the NSF/NIH joint program in mathematical biology (NIH Grant 1R01GM078986-01) is gratefully acknowledged. The Program for Evolutionary Dynamics at Harvard University is sponsored by Jeffrey Epstein. TP gratefully acknowledges support from Society in Science/The Branco Weiss Fellowship.

References
1. Hardin, G. (1968). The Tragedy of the Commons. Science *162*, 1243–1248.
2. Fitter, A. (2005). Common ground. Curr. Biol. *15*, R185–R187.
3. Kareiva, P. (2005). Is the key to conservation changing ethical values or policing unethical behavior? Curr. Biol. *15,* R40–R42.
4. Androutsellis-Theotokis, S., and Spinellis, D. (2004). A survey of peer-to-peer content distribution technologies. ACM Computing Surveys *36*, 335-371.
5. Adar, E., and Huberman, B. (2000). Free Riding on Gnutella. First Monday *5*, http://firstmonday.org/issues/issue5_10/adar/index.html.
6. Hughes, D., Coulson, G., and Walkerdine, J. (2005). Free riding on Gnutella revisited: The bell tolls? IEEE Distributed Systems Online 6.
7. Stallmann, R. (2002). GNU General Public License. http://www.gnu.org/copyleft/copying-1.0.html.
8. Asay, M. (2004). The GPL: Understanding the License that Governs Linux. In Novell Cool Solutions. (http://www.novell.com/coolsolutions/feature/1532.html).
9. Resnick, P., Zeckhauser, R., Friedman, E., and Kuwabara, K. (2000). Reputation Systems. Communications of the ACM *43*, 45–48.
10. Resnick, P., Zeckhauser, R., Swanson, J., and Lockwood, K. (2006). The value of reputation on eBay: A controlled experiment. Exp. Econ. *9*, 79–101.
11. Sugden, R. (1986). The Economics of Rights, Cooperation and Welfare (Oxford: Blackwell).
12. Kandori, M. (1992). Social norms and community enforcement. Rev. Econ. Stud. *59*, 63–80.
13. Leimar, O., and Hammerstein, P. (2001). Evolution of cooperation through indirect reciprocity. Proc. Biol. Sci. *268*, 745–753.
14. Brandt, H., and Sigmund, K. (2005). Indirect reciprocity, image scoring, and moral hazard. Proc. Natl. Acad. Sci. USA *102*, 2666–2670.
15. Nowak, M.A., and Sigmund, K. (2005). Evolution of indirect reciprocity. Nature *437*, 1291–1298.
16. Ohtsuki, H., and Iwasa, Y. (2006). The leading eight: social norms that can maintain cooperation by indirect reciprocity. J. Theor. Biol. *239*, 435–444.
17. Frank, S.A. (1995). Mutual policing and repression of competition in the evolution of cooperative groups. Nature *377*, 520–522.
18. Foster, K.R., and Ratnieks, F.L. (2001). Convergent evolution of worker policing by egg eating in the honeybee and common wasp. Proc Biol Sci 268, 169–174.
19. Hartmann, A., Wantia, J., Torres, J.A., and Heinze, J. (2003). Worker policing without genetic conflicts in a clonal ant. Proc. Natl. Acad. Sci. USA *100*, 12836–12840.
20. Fehr, E., and Gachter, S. (2002). Altruistic punishment in humans. Nature *415*, 137–140.
21. Boyd, R., Gintis, H., Bowles, S., and Richerson, P.J. (2003). The evolution of altruistic punishment. Proc. Natl. Acad. Sci. USA *100*, 3531–3535.
22. Sigmund, K., Hauert, C., and Nowak, M.A. (2001). Reward and punishment. Proc. Natl. Acad. Sci. USA *98*, 10757–10762.
23. Trivers, R. (1971). The evolution of reciprocal altruism. Q. Rev. Biol. 46, 35–57.
24. Axelrod, R., and Hamilton, W.D. (1981). The evolution of cooperation. Science *211*, 1390–1396.
25. Nowak, M.A., and Sigmund, K. (1992). Tit-for-tat in heterogeneous populations. Nature *355*, 250–253.
26. Nowak, M.A., and Sigmund, K. (1993). A strategy of win-stay, lose-shift that outperforms tit-for-tat in the Prisoner’s Dilemma game. Nature *364*, 56–58.
27. Nowak, M.A., and Sigmund, K. (1998). Evolution of indirect reciprocity by image scoring. Nature *393*, 573–577.
28. Camerer, C.F., and Fehr, E. (2006). When does ‘economic man’ dominate social behavior? Science 311, 47–52.
29. Gurerk, O., Irlenbusch, B., and Rockenbach, B. (2006). The competitive advantage of sanctioning institutions. Science *312*, 108–111.
30. Hauert, C., De Monte, S., Hofbauer, J., and Sigmund, K. (2002). Volunteering as Red Queen mechanism for cooperation in public goods games. Science *296*, 1129–1132.
31. Wedekind, C., and Milinski, M. (2000). Cooperation through image scoring in humans. Science *288*, 850–852.
32. Milinski, M., Semmann, D., Bakker, T.C., and Krambeck, H.J. (2001). Cooperation through indirect reciprocity: image scoring or standing strategy? Proc. Biol. Sci. *268*, 2495–2501.
33. Kamvar, S.D., Schlosser, M.T., and Garcia-Molina, H. (2003). The EigenTrust Algorithm for Reputation Management in P2P Networks. WWW2003.
34. Milinski, M., Semmann, D., Krambeck, H.J., and Marotzke, J. (2006). Stabilizing the earth’s climate is not a losing game: supporting evidence from public goods experiments. Proc. Natl. Acad. Sci. USA *103*, 3994–3998.
35. Pfeiffer, T., and Nowak, M.A. (2006). Climate change: all in the game. Nature *441*, 583–584.
36. Milinski, M., Semmann, D., and Krambeck, H.J. (2002). Reputation helps solve the ‘tragedy of the commons’. Nature *415*, 424–426.

Program for Evolutionary Dynamics, Department of Organismic and Evolutionary Biology, and Department of Mathematics, Harvard University, Cambridge, Massachusetts 02138, USA.
E-mail: pfeiffer@fas.harvard.edu