Crowdsourcing, Open Innovation and Collective Intelligence in the Scientific Method: A Research Agenda and Operational Framework

Thierry Buecheler[1], Jan Henrik Sieg[2], Rudolf M. Füchslin[1] and Rolf Pfeifer[1]

[1]Artificial Intelligence Laboratory, Department of Informatics, University of Zurich
[2]Chair for Strategic Management and Innovation, Department of Management, Technology and Economics, ETH Zurich
buecheler@ifi.uzh.ch

Abstract

The lonely researcher trying to crack a problem in her office still plays an important role in fundamental research. However, a vast exchange, often with participants from different fields is taking place in modern research activities and projects. In the "Research Value Chain" (a simplified depiction of the Scientific Method as a process used for the analyses in this paper), interactions between researchers and other individuals (intentional or not) within or outside their respective institutions can be regarded as occurrences of Collective Intelligence. "Crowdsourcing" (Howe 2006) is a special case of such Collective Intelligence. It leverages the wisdom of crowds (Surowiecki 2004) and is already changing the way groups of people produce knowledge, generate ideas and make them actionable. A very famous example of a Crowdsourcing outcome is the distributed encyclopedia „Wikipedia". Published research agendas are asking how techniques addressing "the crowd" can be applied to non-profit environments, namely universities, and fundamental research in general.

This paper discusses how the non-profit "Research Value Chain" can potentially benefit from Crowdsourcing. Further, a research agenda is proposed that investigates a) the applicability of Crowdsourcing to fundamental science and b) the impact of distributed agent principles from Artificial Intelligence research on the robustness of Crowdsourcing. Insights and methods from different research fields will be combined, such as complex networks, spatially embedded interacting agents or swarms and dynamic networks.

Although the ideas in this paper essentially outline a research agenda, preliminary data from two pilot studies show that non-scientists can support scientific projects with high quality contributions. Intrinsic motivators (such as "fun") are present, which suggests individuals are not (only) contributing to such projects with a view to large monetary rewards.

Introduction

The Scientific Method in empirical science is constantly being improved to investigate phenomena, acquire more knowledge, correct and/or integrate previous knowledge. Beyond a constant evolution, several researchers and meta-researchers (e.g., epistemologists and research philosophers) have tried to develop a process view of the main steps conducted in most forms of fundamental research, independent of discipline or other differentiating factors. In the context of this process, many interactions between groups of people and individuals are taking place: e.g., idea generation, formulation of hypotheses, evaluation and interpretation of gathered data, among many others. Furthermore, large project conglomerates (e.g., EU-funded research projects or projects funded through the Advanced Technology Program and others in the U.S., see Lee and Bozeman 2005, p.673ff.) increase the number of such interactions. In many cases, the scientist groups involved self-organize their work and contributions according to their individual strengths and skills (and other measures) to reach a common research goal, without a strong centralized body of control (Melin 2000, Stoehr and WHO 2003, Landry and Amara 1998). The interactions between these individuals and groups can be seen as instances of Collective Intelligence, including consensus decision making, mass communications, and other phenomena (see e.g., Hofstadter 1979).

In what follows, we will select examples of Collective Intelligence, which we base on the following broad definition (Malone et al. 2009, p.2): "groups of individuals doing things collectively that seem intelligent". Collective Intelligence involves groups of individuals collaborating to create synergy, something greater than the individual part (Castelluccio 2006).

Although we will mainly use the generic term "Collective Intelligence", or "CI", we will use an interpretation that is very close to "Crowdsourcing", because we are going beyond the traditional research collaborations (that, of course, are also a form of Collective Intelligence): Crowdsourcing, connoted as "Wikipedia for everything" by the inventor of the term (Howe 2006), has influenced several researchers and practitioners alike. It builds on the concept of User Innovation (von Hippel 1986) among others.

Although there are currently many definitions and similar concepts being discussed in the surrounding space (radical decentralization, wisdom of crowds, peer production, open innovation, mass innovation, wikinomics, and more (Malone 2004, Surowiecki 2004, Benkler 2006, Chesbrough 2003, Leadbeater and Powell 2009, Tapscott and Williams 2008), we will use the following definition of Crowdsourcing:

> "Crowdsourcing is the act of taking a job traditionally performed by a designated agent (usually an employee) and outsourcing it to an undefined, generally large group of people in the form of an open call." (Howe 2010)

For our purposes we understand "Crowdsourcing" as an umbrella term for the nuances indicated by the other terms
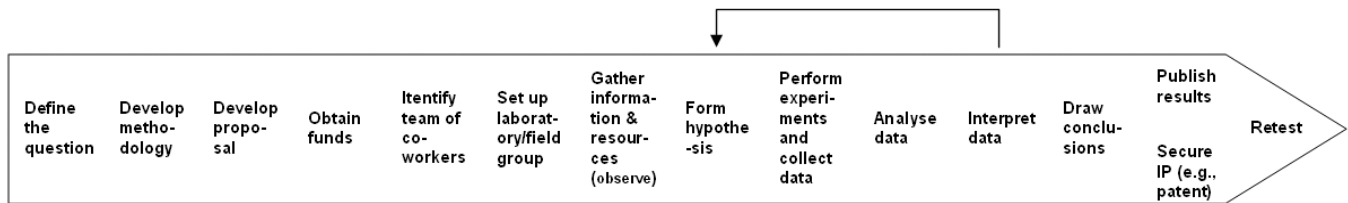
Figure 1 – Simplified Research Process, containing "tasks": the Research Value Chain

Crowdsourcing is a relevant construct for our research because it describes research collaboration that radically enlarges the pool of (potential) scientific collaborators. Research projects, such as NASA's Clickworkers and the "self-organized" research collaboration identifying the cause of the severe acute respiratory syndrome SARS (Stoehr and WHO 2003), go beyond traditional forms of collaboration by embracing electronic communication and cooperation between a very large group of scientists.

The applicability of Crowdsourcing approaches to the solution of scientific problems can be motivated by a simple probabilistic argument: a sufficiently large crowd of independent individuals will, in a majority yes/no vote, decide properly, with high probability, even if the individuals have only a slight bias towards the correct answer. Surowiecki (2004) shows by example that crowd based decision finding also works for questions with answers more complex than yes/no. Moreover, it is known that virtual stock exchanges estimating (betting on), e.g., results of elections deliver surprisingly precise predictions, even if the participants are subject to a broad variety of influences and cannot be regarded as independent. The implementation of Crowdsourcing in a scientific context first requires identifying the type of questions suitable to being answered by a crowd (e.g., strategic decisions that benefit from experience but for which no rational solution scheme exists) and second finding a balance for antagonistic system properties, such as, e.g., communication between agents vs. the independency of their respective decisions. Research areas that provide tools and insights for this optimization task include complex networks, spatially embedded interacting agents or swarms and dynamic networks.

In the following sections, we first propose a simplified process view of the Scientific Method that we use to investigate potential Crowdsourcing opportunities for fundamental research based on the above definitions. Second, we show how mass collaboration (including Crowdsourcing) is already changing the way parties interact in industry and connect this development to science. Third, we develop a framework for analyzing the tasks of the Scientific Method regarding their applicability for Crowdsourcing. After showing some examples from our preliminary analysis, we state important challenges and a research agenda, which investigates these challenges and the applicability empirically.

The Scientific Method as a process

Different fields of research have different approaches to conducting research as a process (see Amigoni et al. 2009 for an example comparing mobile robotics with other sciences). Paul Feyerabend and other well-known meta-scientists

criticize every form of standardization, stating that any depiction has little relation to the ways science is actually practiced (see, e.g., Feyerabend 1993). There are, however, elements that are part of almost every research process (either explicitly or implicitly), such as characterizations, hypotheses, predictions, and experiments. We will use a simplified process for empirical science, based on Crawford and Stucki (1999) as a basis for this paper, which we call the "Research Value Chain" (see Figure 1). "Value" is not defined as economic value, but as an "addition to the body of reliable knowledge", rather a social value.

Not all tasks in our Research Value Chain are present in all research projects: After defining the (research) question at hand, a methodology is either developed or chosen. If necessary, a proposal is compiled to obtain funds or other resources. Potentially, a team of co-workers and a laboratory or field group is set up. Next, resources are gathered, hypotheses are formulated (sometimes implicitly), and subsequently experiments are performed which yield data. The data can then be analyzed and interpreted and conclusions may be drawn that may lead to new hypotheses, indicated by the small connecting arrow in Figure 1. The research piece is then published – or, in some cases, the resulting Intellectual Property (IP) is secured – in order to spread the insights, potentially appropriate the investment and enable other researchers to use it as a basis for their further thinking and testing.

Such a process is potentially subject to iterations, recursions, interleavings and orderings.

Why Crowdsourcing in the Scientific Method

Before answering this question, we need to put Crowdsourcing, a process that is described often in a business (or innovation) context, into a research context. Technological advance has often been subdivided into two categories: invention (a scientific breakthrough) and innovation (commercialization of the invention) - a distinction Nelson and Winter (Nelson and Winter 1982, p.263) attribute to Schumpeter (1934). For this purpose, we demonstrate an important development taking place throughout technologically advancing societies:

Industries are on the verge of a significant change in the way they innovate. Over the past decade, the Internet has enabled communities to connect and collaborate, creating a virtual world of Collective Intelligence (Malone et al. 2009, Lane 2010). Von Hippel (2005) states that for any group of users of a technology, a large number of them will come up with

innovative ideas. What began as a process in business is also being observed in science. Discussions on "Citizen Science" (Irwin 1995) and "Science 2.0" (Shneiderman 2008) suggest the same effects are relevant for fundamental research practices.

Chesbrough provides an example in the consumer sector where a form of Crowdsourcing (in this case, he calls it "open innovation") has proven successful and which seems to be applicable to fundamental research as well:

> "In 1999, Procter & Gamble decided to change its approach to innovation. The firm extended its internal R&D to the outside world through an initiative called Connect and Develop. This initiative emphasized the need for P&G to reach out to external parties for innovative ideas. The company's rationale is simple: Inside P&G are more than 8,600 scientists advancing the industrial knowledge that enables new P&G offerings; outside are 1.5 million." (Chesbrough 2003)

Schrage (2000) states innovation requires improvisation; it is not about following the rules of the game, but more about rigorously challenging and revising them, which is consistent with criticism of any standardization of the Scientific Method. An expert scientist (or an expert group) needs to manage (and perhaps improvise) the overall process and aggregate potential input from "the crowd". But the crowd doesn't necessarily have to be composed of experts.

(Maintained) diversity is an essential advantage of crowds. Scott E. Page has created a theoretical framework to explain why groups often outperform experts. The results of several experiments formed the basis for the "Diversity Trumps Ability" Theorem (Page 2008): Given certain conditions, a random selection of problem solvers outperforms a collection of the best individual expert problem solvers due to its homogeneity. The experts are better than the crowd, but at fewer things. Friedrich von Hayek stated in 1945 that nearly every individual "has some advantage over all others because he possesses unique information of which beneficial use might be made" (von Hayek 1945).

Although certain universities have been trending towards a more entrepreneurial model for more than two decades, (Etzkowitz 1983, Etzkowitz et al. 2000, Bok 2003) we still regard them as being in the not-for-profit field, interested in spreading knowledge throughout society. Crowdsourcing has been successfully used in the business environment for creating economic value. To our knowledge, there is no systematic study investigating the applicability of Crowdsourcing in not-for-profit basic research (as conducted in traditional universities).

This paper aims to help fill this gap by testing the use of Crowdsourcing in the Scientific Method in order to maximize the knowledge that can be gained and dispersed, reduce necessary resources, and other potential contributions to the fundamental research process. Crowdsourcing is regarded as a tool within the Scientific Method, not a substitute for it.

For the remaining sections of this paper, we will use the terms "Collective Intelligence" and "Crowdsourcing" interchangeably for "using a large group of individuals to solve a specified problem or collect useful ideas".

A Framework for integrating Collective Intelligence in the Scientific Method

We combine frameworks from prior research with our own thinking in order to systematically analyze the tasks comprising the Research Value Chain.

The first framework, drawn from MIT's Center for Collective Intelligence (Malone et al. 2009), uses the genome analogy to map the different elements of a Collective Intelligence task to 4 basic "genes": Who, Why, What, How.

These basic questions are further divided into subtypes that help structure the problem at hand in a mutually exclusive, collectively exhaustive manner with respect to Collective Intelligence.
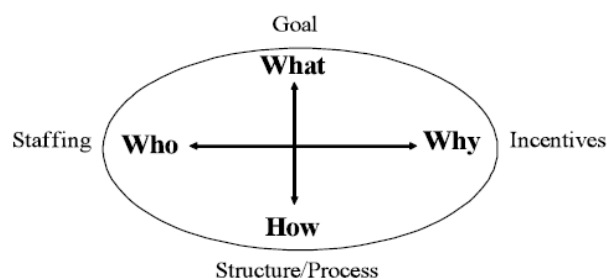
Figure 2 – MIT's Collective Intelligence genes (Malone et al. 2009)

The following list shows the hierarchy of the "genes". For a detailed description, please consult the original paper.

Who
   Crowd, Hierarchy
Why
   Money, Love, Glory
What, How
   Create
      Collection, Contest, Collaboration
   Decide
      Group Decision
         Voting, Averaging, Consensus, Prediction Market
      Individual Decisions
         Market, Social network

However, before a task can be crowdsourced, it needs to be tested as to its suitability for Collective Intelligence. Here we use a design principle called the "Three-constituents principle" from Artificial Intelligence (see e.g., Pfeifer and Scheier 1999). It states that the ecological niche (environment), the tasks at hand and the agent must always be taken into account when investigating or modeling intelligent behavior. Therefore, for every task in our Research Value Chain, we analyze the environment (e.g., research institute location, funding situation), the agent (e.g., researchers'

tenure, culture, particularistic characteristics) and the task. To analyze the likelihood and potential success for collaboration given the environment and the agent, we use the moderating variables identified by Lee and Bozeman (2005).

The following list (not exhaustive) shows variables that moderate the relationship between scientific productivity (normal and fractional journal publications) and collaboration in a scientific setting (several of them backed by other studies):

Agent
Career age, Job satisfaction, Collaboration strategy, "Cosmopolitan scale" (collaborating with those outside the proximate work environment)

Environment
Log of current grants, Field/discipline, Number of collaborators

---

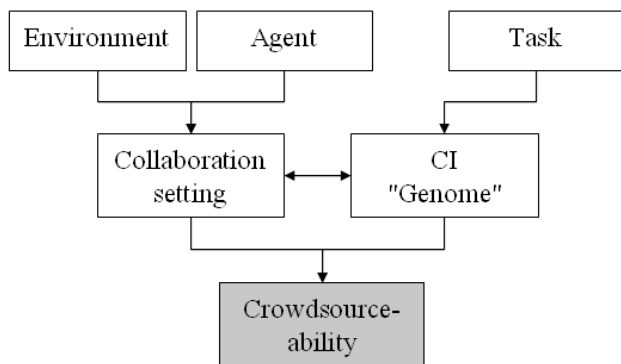Figure 3 gives a schematic overview over all the relationships of the different elements of our framework.

Figure 3 – Framework for assessing Crowdsource-ability of a task

In addition to the potential of crowdsourcing a certain task from the Research Value Chain, we assess its feasibility given limited resources (funding, apparatus, time).

In what follows, we offer a few intuitive examples of where we see untapped potential for Crowdsourcing in the Research Value Chain. We distinguish between "potential" and "feasibility".

Untapped potential for Crowdsourcing within the Scientific Method. Regarding untapped potential, we believe that the analysis of the collected data as well as the interpretation and drawing of conclusions have high potential for using the wisdom of the crowd or rather its intelligence. The crowd is particularly suited for recognizing patterns and important data points ("looking at the right spots"). In addition, the crowd might read data differently, draw additional conclusions and ideas, and thus complement the researcher or a small research team in its findings (evidence can be found in Kanefsky et al. 2001). Another good example

for such a success is the "Goldcorp Challenge" (see e.g., Brabham 2008) The Canadian gold mining group Goldcorp made 400 megabytes of geological survey data on its Red Lake, Ontario, property available to the public over the Internet. They offered a $575,000 prize to anyone who could analyze the data and suggest places where gold could be found. The company claims that the contest produced 110 targets, over 80% of which proved productive; yielding 8 million ounces of gold, worth more than $3 billion. The prize was won by a small consultancy in Perth, Western Australia, called Fractal Graphics.

We see further potential in the formulation of hypotheses (similar to forecasting) from information collected. J. Scott Armstrong of Wharton School studied the prognoses of experts in several fields. In not a single instance could he find any clear advantage in having expertise in order to predict an outcome; "…expertise beyond a minimal level is of little value in forecasting change […].This is not to say that experts have no value, they can contribute in many ways. One particularly useful role of the expert seems to be in assessing a current situation." (Armstrong 1980). In the same paper he states several other studies that confirm this with respect to forecasting or hypothesizing. We also believe that the crowd can be especially useful in defining the (research) questions and in collecting relevant literature. As a positive side effect, consulting a crowd may also help overcome group biases like Groupthink (Janis 1972).

Feasibility of using Crowdsourcing within the Scientific Method. Regarding feasibility, the same steps are likely to be a target for Crowdsourcing: The questions can be discussed and exchanged through electronic channels (e.g., discussion boards, email) and literature collections can be remotely coordinated. Collected data can be posted on the Internet for analysis while interpretations can be discussed through application-sharing tools.

A pilot study was conducted during the "ShanghAI Lectures 2009", (see Hasler et al. 2009), a global lecture on Artificial Intelligence involving 48 universities from five continents – the 421 participating students could support one of four current scientific projects by contributing a paper stating their ideas on pre-defined open questions. The contest prize was a trip for the winning team to Zurich, Switzerland. Some of the solutions were rated "excellent", "well-elaborated" and "useful for the advancement of the project" by the scientists that headed the projects. We sent questionnaires to 372 participating students after the lectures and received 84 valid replies (23%). Although only 16% stated that they had prior theoretical or technical knowledge regarding the chosen subject, 32.1% of them indicated that they had much or very much fun participating in the contest and 15% agreed to participate in another contest while 29% answered "maybe" (although the workload was significant with several hours up to two weeks investment and the lecture was over). 22.6 % of all students (including those that did not participate in the contest) perceived a potential impact on current research if they participated in the contest.

However, the data collection was not thorough enough to analyze all the variables mentioned in our framework.

In addition, data gathered from the Crowdsourcing website "starmind.com" indicates that for 247 not-for-profit scientific questions posted between 1 January 2010 to 27 May 2010, 481 solutions have been submitted by question solvers, 368 of these have been viewed by the question posers with a resulting satisfaction of at least "good" for 267 (73%, on a scale "excellent", "good", "useful", "decline"). 66% of the problem solvers that contributed to a "good" rating are not "scientists" (self-assessed: PhD student, postdoctoral researcher, Professor). Starmind focuses on "small" questions. The rewards for answering a question start as low as EUR 3.-

Our research will analyze the tasks of the Research Value Chain according to the framework in much more depth, aiming to create a CI genome for each task of the Research Value Chain, where applicable. In addition, empirical data will be analyzed regarding the moderating variables to identify relevant sensitivities.

Challenges in Crowdsourcing and the Connection to AI Research

When dealing with any form of outsourcing of tasks (including Crowdsourcing), the risks are non-trivial. Especially for groups that are more distant, geographically and culturally, many situations arise that cannot be foreseen (see e.g., Nakatsu and Iacovou 2009). Crowdsourcing is an extreme case of dealing with the unknown, where emergence and the reactions to emerging behavior play an important role: The individuals of the "crowd" are a priori unknown and contingency plans for unexpected behavior of this interacting mass cannot be fully prepared beforehand. Moreover, in a Crowdsourcing scenario there are no pre-defined contracts between parties like in traditional outsourcing. Lane points out that risk is involved when using Crowdsourcing for decision making:

> "However, mechanisms also need to be in place to protect against competition sabotaging the crowd system. [...] Therefore, systems that leverage the crowd for creation decisions should ensure that the final decision passes through a governing body." (Lane 2010).

Roman (2009) states that there is an inherent weakness to Crowdsourcing that the difference between the "wisdom of crowds" and the "mob that rules" must be actively managed in order to manage correctness, accuracy and other elements that are relevant for valid fundamental research.
(For some further specific risks of Crowdsourcing, see e.g., Kazai and Milic-Frayling 2009).
There is, however, a fundamental consideration that justifies the trust in the wisdom of crowds: Assume that a decision problem has to be tackled. The members of the crowd have a certain intuition about the problem, which gives them a small bias towards the "correct" decision. It is easy to show that if a million individual agents decide independently and have a slight bias of 50.1 % towards taking the right decision (which is close to random guessing), a majority vote will lead to the correct decision with a probability of 97.7%. Even if there is a

lack of expert knowledge, crowd decisions are rather robust. It is an open question to what extent the assumption about the independency of the decisions of individual agents is justified. Furthermore, independency also implies the absence of knowledge transfer between the agents, hardly a desired feature. Finding the optimal balance between communication and independency is therefore a relevant research topic.
Lakhani and Panetta (2007) state when comparing Open Source Software development (OSS) to traditional (business) management:

> "Brownian motion-based management" is not yet taught in any business schools. But the participation of commercial enterprises in OSS communities and other distributed innovation systems suggest that organizing principles for participation, collaboration, and self-organization can be distilled. Importantly, these systems are not "managed" in the traditional sense of the word, that is, "smart" managers are not recruiting staff, offering incentives for hard work, dividing tasks, integrating activities, and developing career paths. Rather, the locus of control and management lies with the individual participants who decide themselves the terms of interaction with each other.

Scholars in Artificial Intelligence (AI) research have developed (and are still developing) "design principles" that distill high-level principles for increasing the robustness of agents or groups of agents (see e.g., Pfeifer and Bongard 2007 or Pfeifer and Scheier 1999). These design principles specifically "prepare" the intelligent agents to deal with unexpected or unknown situations or to interact with unknown environments and large groups or known/unknown individuals.

Three examples of agent design principles

The following three example principles are stated here to make this idea more tangible. The first one deals with the importance of the way a problem is defined for Crowdsourcing, while the second example discusses the need for partial overlaps (redundancy). The third example puts the focus on local rules of interaction, thus shifting the focal point from a complex abstraction of "the crowd" to a better understandable, concrete set of small observations:

'Three Constituents' Principle. The ecological niche (environment), the tasks at hand and the agent must always be taken into account when investigating on or modeling intelligent behavior. This implies for Crowdsourcing, that not only processes or organizational structures (part of the environment) are relevant for success, but also the task (e.g., formulation of the problem at hand) and the socio-technical environment as well as the variables describing the agent (individual, group or other organization) in their interplay. AI research provides frameworks and tools in order to do this systematically. We have already incorporated this principle into our general analysis framework, above.

'Redundancy' Principle. Lean operations (Womack et al. 1991) and other optimizing paradigms are trying to eliminate redundancy in organizational processes. Current Artificial

Intelligence research shows that partial overlap of functionality is helpful and even necessary to build robust intelligent systems that are able to cope with the unexpected and new.

> In general, biological systems are extremely redundant because redundancy makes them more adaptive: if one part or process fails, another, similar part or process can take over. Brains also contain a lot of redundancy; they continue to function even if parts are destroyed. (Pfeifer and Bongard 2007)

Insights from AI research may help identify where redundancy is necessary to create robustness when crowdsourcing, and where it can be omitted for the sake of efficiency.

'Design For Emergence" Principle. This principle specifically aims at Collective Intelligence and states that when analyzing biological systems, the focus should be on the local rules of interaction that give rise to the global behavioral pattern that is studied:

> Because systems with emergent functionality rely on self-organizing processes that require less control, they tend to be not only more adaptive and robust but also cheaper. Emergent functionality requires us to think differently, for example, about social interaction, because much of what we may have thought would be under conscious control turns out to be the result of reflex-like local interactions. (Pfeifer and Bongard 2007)

The local rules of interaction for Crowdsourcing that produce desired input by the crowd are part of our ongoing research. There are many more agent design principles dealing with different numbers of agents (e.g., single agents vs. groups of agents as in a Crowdsourcing situation) and different time scales (e.g. "here and now" vs. ontogenetic and phylogenetic time scales) that we will consider during the analysis that follows.

Making Crowdsourcing in Science more robust – towards a research agenda

In what follows we propose a research agenda that aims at three goals:

G1. Examine which forms (see e.g., Schenk and Guittard 2009) of Collective Intelligence in the large, or Crowdsourcing, and which incentives are suitable for use in fundamental research (based on the simplified "Research Value Chain" and our framework).

G2. Test the applicability of agent design principles in order to make collaboration based on Collective Intelligence more robust, with a special focus on Crowdsourcing in fundamental research.

G3. Identify local rules of interaction between agents in Collective Intelligence interactions (incl. Crowdsourcing) that lead to productive emerging phenomena. The definition of "productive" depends on the domain: In fundamental science it is measured by maximizing the contribution to the body of reliable knowledge.

Research Questions

The following questions will guide our research in the two branches:

G1-Q1. Which forms of Crowdsourcing (e.g., routine task vs. complex task vs. creative) are best suited to fundamental research?

G1-Q2. Are there best practices for Crowdsourcing in fundamental research that can be generalized for several disciplines?

G1-Q3. Which are the best incentive schemes for Crowdsourcing in fundamental research?

G1-Q4. How does the aim of protecting IP with a patent (or other instrument) change the above answers?

G2-Q5. Can the application of agent design principles (e.g., "frame of reference principle", "motivated complexity principle", "cumulative selection principle") to platforms and processes make Crowdsourcing interactions more successful in terms of useful input by "the crowd"?

G2-Q6. If the answer to Q5 is "yes", which design principles are best suited to which situation?

G2-Q7. Are there differences regarding Q6 in different disciplines?

G2-Q8. Decisions made by independent agents are highly robust, but communication offers other benefits. Is there a way to determine an optimal balance between robustness and interdependency/communication?

G3-Q9. Which local rules of interaction can be inferred in different tasks of the Research Value Chain?

Hypotheses

Given the limited data set so far, we state the following hypotheses in order to guide our empirical evidence finding. These hypotheses form a basic collection of ideas that will be subsequently tested, expanded and detailed in a structured and systematic manner.

H1. The prerequisites for Crowdsourcing (see, e.g., Benkler 2006, Howe 2008, Kazman and Chen 2009) are present in academic settings.

H2. Scientists from different disciplines perceive Crowdsourcing as a useful tool for supporting fundamental research.

H3. By systematically applying agent design principles (Three Constituents, Complete Agent, Parallel, Loosely Coupled Processes, Sensory-Motor Coordination, Cheap Design, Redundancy, Ecological Balance, Value) to Crowdsourcing settings, the output of the community (in terms of "value" as judged by seeking scientists) can be significantly increased (compared to not applying principles).

H4. By systematically applying design principles for development (Integration of Time Scales, Development as an Incremental Process, Discovery, Social Interaction, Motivated Complexity) and insights from AI fields (e.g., Swarm Behavior, Complex Networks), the quality of a community can be improved over time in terms of efficiency and effectiveness in solving a crowdsourced task (compared to groups not applying principles).

H5. By systematically applying design principles for evolution (Population, Cumulative Selection and Self-Organization,

Brain-Body Coevolution, Scalable Complexity, Evolution as a Fluid Process, Minimal Designer Bias), a research group can increase its value creation (see above) from Crowdsourcing processes over time quicker than when not applying the principles.

H6. Crowdsourcing techniques allow Academic research groups to more successfully advance outputs from fundamental research to market maturity (technology transfer) than without Crowdsourcing.

H7. "Crowds" (in the sense of an active community in Crowdsourcing) involved in fundamental research are subject to guided self-organization (i.e., autonomous global self-organization with a few adjustable parameters, e.g., given by the environment or the platform).

Methods and Approaches

We will apply our framework to identify the sensitivities regarding moderating variables (environment and agent) when in a fundamental research setting. In addition, we will generate "CI genomes" for each task in the Research Value Chain, in order to better understand the applicability for Crowdsourcing. In parallel, we will collect more data regarding Crowdsourcing contributions to different steps in the "Research Value Chain":

The data gathering will consist of several Crowdsourcing contests treating current projects in fundamental research (at universities). Both the participants in the contests ("crowd") as well as the participating researchers will complete a set of questionnaires which include both closed- and open-ended questions on individual and team functioning (in case a contribution is made by a team) during these contests as well as self-assessed vs. outside-assessed ratings of the inputs they give. The questionnaires will be based on (Bartl 2006) and (Lakhani et al. 2006), but slightly adapted to better suit the non-profit context of universities.

One (or more) iteration(s) of the data gathering process will be used to (in)validate the insights gained from the data and test the application of agent design principles as stated above.

As a final measure, a Multiagent System (Weiss 2000, Wooldridge 2008) will be implemented in order to simulate stochastic behavior given the sensitivities and settings found in the data.

The inquiry will limit its focus to fields where the "Research Value Chain" is applicable and generally accepted as a guiding process for conducting fundamental research.

Conclusion

Based on the current success in several industries, we see indications that fundamental research potentially benefits from leveraging Collective Intelligence techniques (including Crowdsourcing). We hypothesize that there are "tasks" in the Scientific Method that can potentially benefit from Crowdsourcing and will test our hypotheses according to the stated research agenda.

In addition, we will test the applicability of agent design principles from Artificial Intelligence research to Crowdsourcing. In this paper, we have shown only a few examples of these principles, there are more stated in the current AI literature (The hypotheses H3 to H5 state some more principles that might be suitable for this context.) Although focusing on fundamental science, this research will potentially yield insights for making processes involving Collective Intelligence in the private sector more robust, too. If you would like to be part of this research, please contact the corresponding author.

References

Amigoni, F., M. Reggiani, V. Schlaffonati. 2009. An insightful comparison between experiments in mobile robotics and in science. *Autonomos Robot*(27) 313–325.

Armstrong, J. S. 1980. The seer-sucker theory: The value of experts in forecasting. Technology Review 83: 18-24. *Technology Review* **83** 18–24.

Bartl, M. 2006. *Virtuelle Kundenintegration in die Neuproduktentwicklung.* Deutscher UniversitSts-Verlag | GWV Fachverlage GmbH Wiesbaden, Wiesbaden.

Benkler, Y. 2006. *The wealth of networks. How social production transforms markets and freedom.* Yale Univ. Press, New Haven.

Bok, D. C. 2003. *Universities in the marketplace. The commercialization of higher education.* Princeton Univ. Press, Princeton.

Brabham, D. C. 2008. Crowdsourcing as a Model for Problem Solving. *Convergence: The International Journal of Research Into New Media Technologies* **14**(1) 75–90.

Castelluccio, M. 2006. Collective Intelligence. Editor's comment. *Strategic Finance*(Tech Forum) 51–52.

Chesbrough, H. W. 2003. *Open innovation. The new imperative for creating and profiting from technology.* Harvard Business School Press, Boston.

Crawford, S., L. Stucki. 1999. Peer review and the changing research record. *Journal of the American Society for Information Science* **41**(3) 223–228.

David, P. A. 2004. Can "Open Science" be Protected from the Evolving Regime of IPR Protections? *Journal of Institutional and Theoretical Economics JITE* **160**(1) 9-34(26).

Etzkowitz, H. 1983. Entrepreneurial scientists and entrepreneurial universities in American academic science. *Minerva* **21**(2-3) 198–233.

Etzkowitz, H., A. Webster, C. Gebhardt, B. R. Cantisano Terra. 2000. The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. *Research Policy* **29**(2) 313–330.

Feyerabend, P. K. 1993. *Against method,* 3rd ed. Verso, London.

Hasler, B. S., T. Buecheler, R. Pfeifer. 2009. Collaborative Work in 3D Virtual Environments: A Research Agenda and Operational Framework. A. A. Ozok, P. Zaphiris, eds. *Online communities and social computing. Third international conference, OCSC 2009, held as part of HCI International 2009, San Diego, CA, USA, July 19-24, 2009 ; proceedings.* Springer, Berlin, 23–32.

Hofstadter, D. R. 1979. *Gödel, Escher, Bach: An Eternal Golden Braid.* Basic Books.

Howe, J. 2006. The Rise of Crowdsourcing. *WIRED Magazine*(14.06), http://www.wired.com/wired/archive/14.06/crowds.html

Howe, J. 2008. *Crowdsourcing: Why the Power of the Crowd is Driving the Future of Business.* Crown Publishing, New York.

Howe, J. 2010. Crowdsourcing. Why the Power of the Crowd is Driving the Future of Business, http://www.crowdsourcing.com/ (April 3, 2010).

Irwin, A. 1995. *Citizen science. A study of people, expertise and sustainable development.* Routledge, London.

Janis, I. L. 1972. *Victims of groupthink. A psychological study of foreign-policy decisions and fiascoes.* Houghton Mifflin, Boston.

Kanefsky, B., N. G. Barlow, V. C. Gulick. 2001. Can Distributed Volunteers Accomplish Massive Data Analysis Tasks? *32nd Annual Lunar and Planetary Science Conference, Houston, Texas.*(1272).

Kazai, G., N. Milic-Frayling. 2009. On the Evaluation of the Quality of Relevance Assessments Collected through Crowdsourcing. *Proceedings of the ACM SIGIR 2009 workshop on the future of IR evaluation*.

Kazman, R., H.-M. Chen. 2009. The Metropolis Model: A New Logic for Development of Crowdsourced Systems, http://cacm.acm.org/magazines/2009/7/32094-the-metropolis-model-a-new-logic-for-development-of-crowdsourced-systems/fulltext (April 5, 2010).

Landry, R., N. Amara. 1998. The impact of transaction costs on the institutional structuration of collaborative academic research. Research Policy 27(9) 901–913.

Lakhani, K. R., L. B. Jeppesen, P. A. Lohse, J. A. Panetta. 2006. The Value of Openness in Scientific Problem Solving. *Harvard Business School*(HBS Working Paper Number: 07-050).

Lakhani, K. R., J. A. Panetta. 2007. The Principles of Distributed Innovation. *MIT innovations* **2**(3) 97–112.

Lane, S. 2010. Collective Intelligence for Competitive Advantage: Crowdsourcing and Open Innovation. *Applied Information Management Master's Capstone Projects and Papers*, https://scholarsbank.uoregon.edu/xmlui/handle/1794/10210.

Leadbeater, C., D. Powell. 2009. *We-think. mass innovation, not mass production.* Profile, London.

Lee, S., B. Bozeman. 2005. The Impact of Research Collaboration on Scientific Productivity. *Social Studies of Science* **35**(5) 673–702.

Malone, T. W. 2004. *The future of work. How the new order of business will shape your organization, your management style, and your life.* Harvard Business School Press, Boston.

Malone, T. W., R. Laubacher, C. Dellarocas. 2009. Harnessing Crowds: Mapping the Genome of Collective Intelligence. *MIT Sloan Research Paper*(4732-09).

Melin, G. 2000. Pragmatism and self-organization Research collaboration on the individual level. *Research Policy* **29**(1) 31–40.

Nakatsu, R. T., C. L. Iacovou. 2009. A comparative study of important risk factors involved in offshore and domestic outsourcing of software development projects: A two-panel Delphi study. *Information & Management* **46**(1) 57–68.

Nelson, R. R., S. G. Winter. 1982. *An evolutionary theory of economic change.* Belknap Press of Harvard Univ. Press, Cambridge.

Page, S. E. 2008. *The difference. How the power of diversity creates better groups, firms, schools, and societies,* 3rd ed. Princeton Univ. Press, Princeton, NJ.

Pfeifer, R., J. Bongard. 2007. *How the body shapes the way we think. A new view of intelligence.* MIT Press, Cambridge.

Pfeifer, R., C. Scheier. 1999. *Understanding intelligence,* 1st ed. MIT Press, Cambridge.

Roman, D. 2009. Crowdsourcing and the question of expertise. *Communications of the ACM* **52**(12) 12.

Schenk, E., C. Guittard. 2009. Crowdsourcing: What can be Outsourced to the Crowd, and Why? HAL: Sciences de l'Homme et de la Société. *halshs.archives-ouvertes.fr*.

Schrage, M. 2000. *Serious play. How the world's best companies simulate to innovate.* Harvard Business School Press, Boston.

Schumpeter, J. A. 1934. *The theory of economic development. An inquiry into profits, capital, credit, interest, and the business cycle.* Transaction Books, New Brunswick.

Shneiderman, B. 2008. Science 2.0. Copernican challenges face those who suggest that collaboration, not computation are the driving energy for socio-technical systems that characterize Web 2.0. *Science* **319** 1349–1350.

Stoehr, K., WHO. 2003. A multicentre collaboration to investigate the cause of severe acute respiratory syndrome. *The Lancet* **361**(9370) 1730–1733.

Surowiecki, J. 2004. *The wisdom of crowds. Why the many are smarter than the few and how collective wisdom shapes business, economies, societies, and nations,* 1st ed. Doubleday, New York.

Tapscott, D., A. D. Williams. 2008. *Wikinomics. How mass collaboration changes everything.* Portfolio, New York.

von Hayek, F. A. 1945. The Use of Knowledge in Society. *American Economic Review* 519–530.

von Hippel, E. 1986. Lead Users: A Source of Novel Product Concepts. *Management Science* **32**(7) 791–805.

von Hippel, E. 2005. *Democratizing innovation.* MIT Press, Cambridge.

Weiss, G., ed. 2000. *Multiagent systems. A modern approach to distributed artificial intelligence,* 2nd ed. MIT Press, Cambridge.

Womack, J. P., D. T. Jones, D. Roos. 1991. *The machine that changed the world. [the story of lean production],* 1st ed. Harper Perennial, New York.

Wooldridge, M. J. 2008. *An introduction to multiagent systems.* Wiley, Chichester.