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Collaboration and reward

What do we measure by co-authorships?

Grit Laudel

Interviews with scientists about the content and reward of collaborations, and classification of contributions of co-authors and scientists cited in acknowledgements, identified six types of research collaborations with distinct patterns of rewards; showed that about half of the collaborations are invisible in formal communication channels because they are not rewarded; and showed that about one third of the collaborations are rewarded only by acknowledgements.

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IN BIBLIOMETRIC STUDIES, research collaborations are usually measured by co-authorships. This ubiquitous practice rests on certain assumptions that are sometimes explicitly discussed in 'methodology' sections but seem to be of no consequence for the interpretation of data. A first assumption is that all people who appear as a paper's co-authors actually took part in the research collaboration. This assumption is sometimes called into question by the observation that some authorships are not based on collaborative contributions as, for example, with honorary co-authors (Katz and Martin, 1997, page 3), and that this phenomenon seems to be a serious problem in some fields as, for example, with biomedicine (Biagioli, 1999, pages 17–21). However, these errors can be handled statistically (Melin and Persson, 1996, page 365).

A second assumption that accompanies bibliometric studies of collaboration ever since the famous papers of Beaver and Rosen (1979a-c) is usually implicit: it is assumed that all scientists who collaborate become co-authors (Gordon, 1980, page 194). Explicitly methodological contributions have recognised that this assumption is questionable because co-authorships do not depict all collaborative relations but only a certain fraction (e.g. Edge, 1979, page 121; Katz and Martin, 1997, pages 2–3; Van Raan, 1998a, page 424). Unfortunately, this observation has not been substantiated by information about what is not covered. Even more regrettable is that empirical bibliometric studies of collaboration in science do not take into account these methodological warnings and focus instead on measuring collaborations in terms of co-authorships.

So far, only one empirical study has included the question of how collaborative research is related to co-authorships. Melin and Persson asserted that 'when we infer co-authorships to collaboration we

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are running the risk of neglecting some collaborations as well as being insecure about the actual reasons behind co-authorships' (Melin and Persson, 1996, page 364). Finding from a small-scale survey that only 5% of the authors had experienced situations in which collaboration did not result in co-authored papers, and that these cases were caused by low importance being attached to the collaborative contributions in question, Melin and Persson conclude that 'there is hardly a tendency for collaboration to be underrepresented when studying co-authorships' (Melin and Persson, 1996, page 365).

This result clearly contradicts my own findings from an extensive qualitative study on interdisciplinary research collaboration (Laudel 1999, 2001b). In this study, I investigated how a specific institution (the so-called Collaborative Research Centre [CRC]) promotes interdisciplinary collaboration.[1] To do this, the varieties of research collaboration undertaken between 57 German research groups in two CRCs in an interdisciplinary field covering the borders between biology, physics and chemistry were explored. It contained subfields such as molecular and cell biology, biophysics, physical and organic chemistry, biochemistry, theoretical physics, polymer research, microscopy and spectroscopy. The interdisciplinary field refers to a complex research object whose investigation requires the application of methods from all these subfields.[2] Qualitative and quantitative data on 322 collaborations found in the CRCs suggest that there are many variants of research collaboration that are not covered by co-authorships, i.e. that the bibliometric indicator 'co-authorship' is systematically biased against some collaborative practices.

The aim of this paper is to question the aforementioned assumptions underlying bibliometric studies by answering three questions:

- What types of collaborations lead to co-authorships?
- Under what conditions are co-authorships granted?
- What role do other forms of rewarding collaborative contributions play?

These considerations shall not invalidate the indicator 'co-authorship' but contribute to a 'micro-theory' of that indicator. Van Raan has stated with regard to citation analyses that we need a 'statistical approach in terms of distribution functions' of citers' individual characteristics (Van Raan, 1998b, page 136). Similarly, a theory is necessary that supports interpretations of co-authorships by explaining the connections between variation of collaboration and variation of rewards (among them co-authorships). To construct empirically grounded theories of this type, bibliometric methods must be supplemented by qualitative methods (Harsanyi, 1993, page 340; Mählck and Persson, 2000, page 90). The empirical results presented here result from such an integrated approach. They will be used as a contribution to a micro-theory of collaboration.

Theory, methodology and methods

Any empirical study of research collaboration has to cope with the subject's fuzziness. Asking scientists themselves what a collaboration is quickly leads to confusion:

> 'Well, I would it call a collaboration if something written comes out of it that is published together.'
>
> 'And there are many colleagues with whom I collaborate without direct results in the form of joint publications, but we help each other and maintain relations.'
>
> 'H had tried for a long time to isolate a protein and didn't succeed. Then S asked E to give us the recipe.'
>
> '… additionally the chemists provide advice, they look at the physicists' substances.'
>
> 'We agreed that I take a group from his field into the NMR-department, that means that I give them the opportunity to use the equipment.'

The five scientists pointed to quite different activities. If a study on collaboration is based upon the view quoted first, a nice match of collaboration and co-authorship is likely. Thus, the results reported by Melin and Persson are probably caused by the question 'whether jointly achieved results were published individually' they used in their survey (Melin, 2000, page 35). However, if the other statements are taken into account, it becomes clear that we cannot base empirical studies on scientists' implicit understanding of collaboration.

The theoretical literature mirrors the empirical fuzziness. Katz and Martin even argue that it is impossible to define research collaboration:

> A research collaboration […] has a very 'fuzzy' or ill-defined border. Exactly where that border is drawn is a matter of social convention and is open to negotiation. Perceptions regarding the precise location of the 'boundary' of the collaboration may vary considerably across institutions, fields, sectors and countries as well as over time. (Katz and Martin, 1997, page 8)

Nevertheless, any empirical investigation ultimately rests on a definition of the phenomenon under investigation. We are only left with the alternative of either working with implicit definitions or formulating an explicit (albeit incomplete) definition.

In the theoretical literature I found a confusing variety of definitions (for a detailed discussion, see Laudel, 1999, pages 29–35). The study presented here was based upon some theoretical decisions; collaboration was regarded as a phenomenon related to the functional level of collective action by individual, collective or corporate actors who do not necessarily have a common goal. These considerations resulted in the following definition: 'A research collaboration is defined as a system of research activities by several actors related in a functional way and coordinated to attain a research goal corresponding with these actors' research goals or interests' (Laudel, 1999, page 32). Important consequences of this definition are:

- A shared research goal is not a necessary presupposition for collaboration. An actor may collaborate according to their interests; for example, they may be interested in conforming to a collaboration norm and hence in helping another scientist.
- Collaboration is defined by the activities rather than by the actors involved. Thus it can be decided whether fundraisers, technical assistants or other people contributing to the collaboration's success are collaborators. Faced with this problem, Katz and Martin refused to define research collaboration and presented only a kind of checklist of who should be regarded as collaborator. The reasons for including these people and excluding others are not comprehensible (Katz and Martin, 1997, pages 7–8). Following from the definition presented here, people are collaborators if they conduct *research activities* — 'actions that are aimed at the production of new scientific knowledge' (Krohn and Küppers, 1990, page 211).
- The concept collaboration is strictly reserved for research that includes personal interactions. Thus, formal communication and references to other scientists are regarded as a different phenomenon. While all scientific research is collaborative in certain respects because it makes use of the work of other scientists, collective knowledge production based on formal communication differs from immediate collaboration in its social dynamics, especially in the way actions are coordinated (Gläser, 2001).

On the basis of the aforementioned definition, it was possible to design an empirical investigation of research collaboration that combined quantitative and qualitative methods. The main method was a qualitative analysis based upon 101 semi-structured interviews with research group leaders and at least one group member; that is, a postdoctoral researcher or a PhD student. Both group leaders and group members were asked to give an account of all their collaborations with other CRC groups and of their most important external collaborations. For all CRC collaborations, the information gathered concerned:

- the reasons why the collaborations were started and finished;
- the collaborations' course, especially about the different partners' contributions; and
- the promoting and inhibiting conditions.

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Moreover, each interviewee was asked to give a detailed description of their current research work. Group members in particular were asked carefully to describe their whole research process. Additionally, some interviewees were asked about the course of the publishing process of the collaborative work. The interviews were accompanied by non-systematic observations in some laboratories and during scientific meetings of the CRCs. These observations allowed me to study concrete collaborations — such as transmission of know-how — as well as coordinating activities, representation of the collaborations' results and the rules governing coordination and collaboration.

By looking up the research groups' publications in the *Science Citation Index* (SCI) (CDROM Version), co-authorships were identified and used as an additional indicator to study collaborations. Furthermore, a content analysis of acknowledgements in PhD theses was conducted. Both co-authorships and acknowledgement analysis were used in order to identify collaborations, contributions of the respective partners and forms of rewards.

In order to substantiate the claims of this paper, additional empirical analyses have been conducted. All articles listed by one collaborative research centre (with 20 research groups) as reporting experimental results of a three-year funding period were collected. All these articles were covered by the SCI. Theoretical articles and reviews were excluded. A content analysis of acknowledgements in these articles was conducted with respect to the collaborative contributions that were reported. Additionally, the institutional affiliation of all co-authors was identified on the basis of SCI address fields, Internet searches and information from interviews.

Thus, for each article the following information was obtained:

- name of the CRC research group;
- names and locations (same group, same organisation, external/national, external/international) of all co-authors and persons mentioned in the acknowledgements; and
- content and type of collaboration.

Results

By combining qualitative and quantitative (bibliometric) methods, an almost complete overview of a certain proportion of the CRC's collaborations could be achieved. Observations and interviewees' detailed descriptions of their research enabled me empirically to distinguish the types of collaborative work found in experimental research. As bibliometric analyses and content analyses show, the ways in which these different contributions were rewarded varied systematically. Both interviews and observations led to the identification of global and local rules as well as practices of rewarding that are responsible for the variations. The scope of my findings encompasses experimental research in the natural sciences, undertaken in small groups.

Variations of collaboration

In the bibliometric literature we usually find collaboration types constructed by the criteria of the contributors' institutional affiliation (intra-research group, intradepartmental, international, etc.; e.g. Katz and Martin, 1997, pages 9–10; Katz and Hicks, 1997; Bordons *et al*, 1996; Hinze, 1999). Though these distinctions may be important for purposes of evaluation, they are of little use when it comes to studying relations between the content of collaborative work and the ways this work is rewarded. For the task described here, criteria related to the content of contributors' research actions must be chosen (as it was in the original study). Interviewees' descriptions of collaborative contributions to research work made and received by them enabled several types of collaboration to be distinguished.

In all the research processes that have been investigated, some necessary basic activities could be identified:

- formulation of a research question;
- preparation of the research object;
- development or adaptation of one or several research methods;
- measurement itself (production of data); and
- interpretation of the data.

Within research processes, collaboration took place if these basic activities were conducted as the specialised tasks of different researchers. I will first describe the various forms of specialisation and the types of collaborations constructed on these grounds. Two other types of collaboration were not based on specialised contributions.

A first specialisation that has been observed occurs between 'thinking' and 'experimental craft'; that is, between theoretical and conceptual activities, on the one hand, and experimental activities, on the other hand. It is mainly caused by the rapidly changing dynamics of many research fields, and is promoted by the pressure permanently to raise funds along with the abundance of doctoral students as low-paid research workers. As a rule, the group leader no longer conducts experimental work, because of a lack of time. To monitor a research field's development, to design research projects and to seek funding possibilities are time-consuming tasks. Since experimental techniques develop and diversify rapidly, considerable time is required to learn and apply at least some of them. Consequently, there is not enough time to carry out experimental and theoretical work simultaneously. Because only the group leader is able to conduct the conceptual and theoretical work, they tend to focus exclusively on this.[3] It involves:

- studying the literature from the specific research field and some neighbouring fields;
- developing concepts and formulating research questions; and
- designing projects and acquiring funds.

Empirical (i.e. experimental) work is conducted by the other group members, mostly doctoral students. These scientists are strongly involved in selecting and adapting the experimental methods for solving research problems. To do this, they mainly study literature directly related to their current experimental process; that is, literature containing information about the current research objects' properties, new methodical and instrumental developments, alternative methods and so on. Their time-consuming experimental work leaves them unable to pursue the literature of the whole problem area, which is why wider theoretical knowledge was observed to be held by the group leader.

The interpretation of the experimental data requires theoretical as well as methodical knowledge and, thus, the combination of the group leader's and the doctoral student's knowledge. For these reasons, both researchers interpreted the data together. The group leader generalises results and integrates them into the field's current body of knowledge. Subsequently, group leader and the group members who conducted the experimental work together publish the results.

This form of collaboration has been described in the literature, with regard to the social relations involved, as apprenticeship or teacher/student-relationship (Edge, 1979, page 106) or teacher-pupil collaboration (Subramanyam, 1983, page 34). Peters and Van Raan described it by examining co-authorships in a university department of chemical engineering by means of an additional qualitative analysis. They found that 'co-authors may include postdoctoral fellows, postgraduate students, technicians and others, who have worked under the supervision of a senior scientist' and that most of their clusters represent such research groups (Peters and Van Raan, 1991, page 246). These observations correspond to the differentiation of the content of work that is used here.

The division of labour between conceptual and experimental work can be said to be based upon *vertical* specialisation. Since it was found to accompany all observed research processes, it made no sense to use it as a specific type of collaboration. *Horizontal* specialisation of scientists is a very general phenomenon that refers to scientists' different expertise. Consequently, it occurs at both levels of vertical specialisation; that is, on the theoretical-conceptual (group-leader) level as well as on the experimental (doctoral student) level. The necessity to combine expertise from different research areas in approaching problems and, consequently, interpreting data, requires the collaboration of group leaders, which is often accompanied by collaboration on the experimental level. On that level, a specialisation of preparation techniques and measurement techniques takes place. Moreover, sometimes preparation or measurement techniques from more than one research field are required. In both cases the scientists must collaborate in the experimental process. Depending on what contributions are required from other fields, different types of resulting collaborations can be distinguished (see Figure 1).

Collaboration involving a division of labour (DOL) was found to be characterised by a shared research goal and a division of creative labour between the collaborators. This type of collaboration occurred if both the theoretical-conceptual and the experimental work required contributions by more than one researcher. The collaboration spanned all phases of the research process. The research process began with the joint formulation of the research problem. Thereafter, one researcher prepared the research object; that is, synthesised substances, purified proteins, cultivated cells and so on. The properties of the prepared object were investigated by the second researcher who had developed or adopted a suitable method. As is to be expected, both group leaders and two doctoral students were usually involved in a collaboration of this type.[4] Their activities were closely inter-linked. However, a special form of such collaboration occurred in some cases when the experimental work was realised by only one doctoral student who was supervised by both research groups' leaders. The student belonged to both groups and had to create the connection between the two. In this case the creative work was also divided between both research groups, because the group leaders had to be involved in the formulation of the problem and the interpretation of the results.

In a *service collaboration* (SER), the research goal was set by one of the collaborators alone, and they performed all the creative work. Although possibly substantial and time-consuming, the other collaborators' contributions were routine. This type of collaboration occurred when contributions such as the preparation of research objects or measuring had become a routine but required expertise; for example, preparation of proteins, cell mutants, genetically modified organisms or the production of electron microscopical data. Service collaborations are generally necessary if the researcher cannot learn the methods required to solve the problem because the learning process would be too time-consuming or because they lack the necessary knowledge to learn the method.

The investigated service collaborations were usually brought about by the interdisciplinary nature of the research processes. Service collaborations often occurred when one scientist wished to test whether specific methods were appropriate for the problem solving. To learn the method would have been useful only if the test produced a positive result. The collaborator who performed the service did not influence the formulation of the research problem. They had their own research goals, which were different from that of the scientist who obtained their service. This difference implies that service collaborations are only carried out if they are not too time-consuming.

An even weaker type of collaboration is the *provision of access to research equipment* (ARE). Here, the collaborator was found not to carry out the routine work required, but only to provide access to the necessary research equipment in their laboratory. Activities were restricted to giving the researcher an introduction to the equipment and providing ongoing

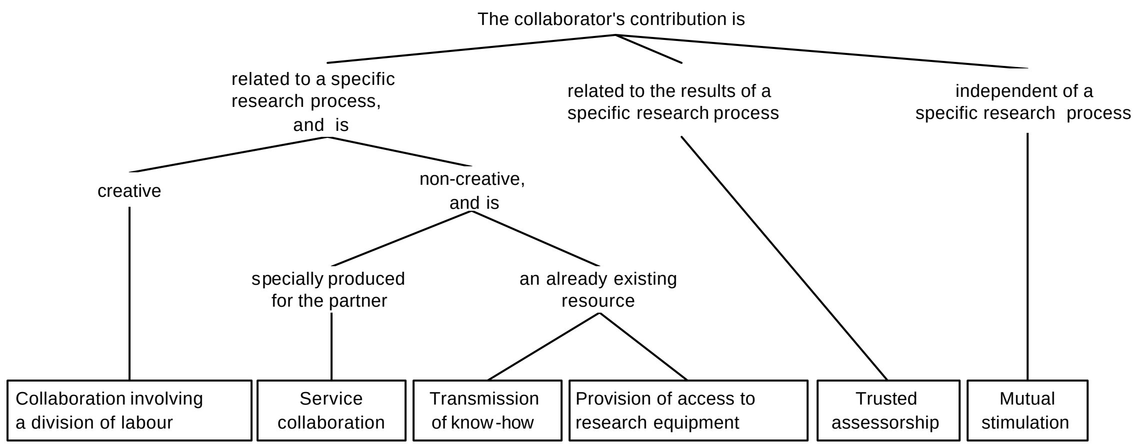

Figure 1. Construction of collaboration types according to horizontal specialisation and non-specialised contributions

assistance if necessary. The guest also benefited from the host's responsibility towards maintaining the research equipment. All these activities had a routine character for the group that 'owns' the research equipment and had nothing to do with the group's own research processes and goals. In contrast to DOL and SER, the whole research process was concentrated in one research group. This type of collaboration was often chosen when the method could be easily learned; that is, if it required only minimal manual-technical knowledge (e.g. fluorescence microscopy or dynamic light scattering).

> We used some equipment in S's lab … These are routine instruments … where you get a half-hour introduction and then you can do it yourself.

The fourth type of collaboration is the *transmission of know-how* (TKH). As the term 'know-how' suggests, what was transmitted was procedural knowledge; that is, knowledge that is required to engage successfully in a specific research process, such as knowledge about features of the research object or about approaches in applying methods. The transmission of knowledge was often the result of a request made by a researcher who needed a colleague's special knowledge efficiently to solve problems that suddenly occurred in experimental work. This kind of collaboration is necessary because it is impossible to describe all experimental details in a paper. The transmissions of know-how observed in my empirical investigation were often a response to spontaneous requests, these sometimes being stimulated by scientific meetings. Scientists who passed on their knowledge had it in their memory, by which is meant that imparting this kind of knowledge is a non-creative activity that supports a colleague's research process.

> We attended a conference in M … There somebody gave me a very, very valuable tip on how the layers remain stable, how they are produced without disintegrating thereafter.

Beside these four types of collaboration that rest upon horizontal specialisation, two other forms were

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frequently observed. Both are not necessarily bound to specialisation; that is, they may occur within as well as between fields. The first of these forms and thus the fifth type of collaboration is *mutual stimulation* (MUS). This type is also different from the previous four in that it is not related to a single research process and does not contain an exchange of clearly defined contributions. Mutual stimulation is a side effect of scientific communication and therefore related to the scientists' research work as a whole, to their respective research programmes or even simply to the work of colleagues. The communication between scientists may stimulate them to think about unsolved problems in their field, about possible new research projects, about the interpretation of older data and the like. In this process of thinking accompanying every personal scientific communication, scientists may develop new ideas about problems, solutions and so on. In contrast to the fourth type — the transmission of know-how — the important contribution is not the knowledge that is passed on, but its function of stimulating the creativity of one or both partners. A famous example of mutual stimulation is quoted by Maini and Nordbeck (1973, page, 192):

> As with Watson, so with Brenner, Crick discussed ideas and plans for experiments day after day. They never collaborated in the sense of doing experiments together at the same time … their particular research interests have been complementary … They interrupt each other, to continue either in 'dialogue' or 'duologue', the ideas tumbling helter-skelter from Crick to be met by a relentless questioning from Brenner.

Because of its fuzzy and spontaneous character MUS could not be systematically observed or discussed in interviews. Therefore, all accounts and descriptions of it are incomplete.

While the five types of collaboration described so far are all connected with the process of knowledge production itself, a sixth type — *trusted assessorship* (TRA) — refers to the process of publishing results (Chubin, 1975; see also Heffner, 1981, page 6; Patel, 1973). This type of collaboration was introduced by Mullins, who coined this term to describe those colleagues who act as accepted and friendly critics (Mullins, 1973, page 18).

> That starts already with the formulation. When I described a picture obtained by electron microscopy, this was incomprehensible for an expert. An expert had said at once that the author did not know his subject because he describes only what he sees in the picture without knowing how it is produced … And when I had written something I gave it to somebody in the [electron microscopy lab] — Read this! Can I write it this way? (a chemist, using electron microscopy as a new method)

Some of the collaboration types often accompanied each other. For instance, ARE was always associated with supporting activities (i.e. SER) if the equipment involved was complicated. DOL often included TKH because the knowledge of the separate activities must be brought together. Similarly, ARE required TKH. DOL usually included an element of MUS because new ideas emerged in the collaboration process.

> Some ideas you get only when you simply discuss intensively with one another … so, through more in-depth discussions you hit upon things that you'd simply never thought of before. Because you then also see the contradictions and want to get to the bottom of them. (a group leader on discussions during a DOL)

The collaboration type may change during the research process. Some of the observed SER changed into ARE when the test of methods was successful and their subsequent application time-consuming. A SER might also change into a DOL when the interests of the collaborator providing the service changed and a shared research goal emerged.

Collaboration types (except TRA) were constructed with the qualitative and quantitative information on the more than 300 single collaborations. Additionally, these data were used to analyse the network structure of CRC inter-group collaborations. Figure 2 shows one CRC's collaboration network that included all collaborations that could be identified reliably enough to count them; that is, the types based upon horizontal specialisation. (MUS could not be included systematically because of its volatile character, and TRA was obtained from the literature after the first empirical investigation.) For reasons that will become clear in the following section, a distinction between DOL and all other types (which can be subsumed under the term 'supporting collaborations') was made. The figure shows clearly that the network is shaped by both DOL and supporting collaborations. Some research groups are linked to the network exclusively by supporting collaborations.

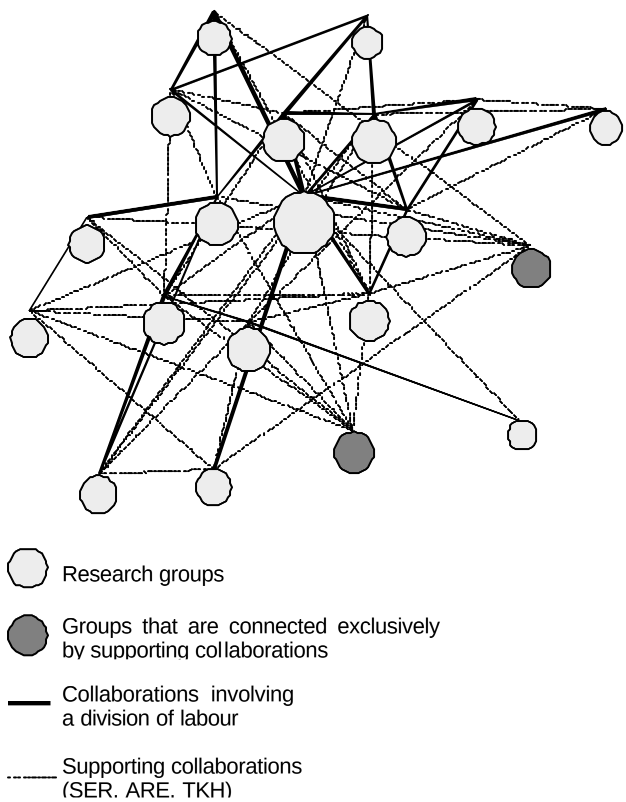

Figure 2. Collaborations of one CRC's research groups during one three-year interval[6]

For the following analysis of relations between collaborative contribution and rewards, collaboration data represented by Figure 2 were selected. Thus, the analysis uses data on one CRC and one time interval.[6]

Variations of rewards

The question of how the different types of collaborations were rewarded was answered by bibliometric and content analyses of publications. These analyses were conducted in two directions. In a first step, the published results of a subset of collaborations were examined. The analysis provided an answer to the question as to whether and how the observed collaborations were rewarded in formal communication channels. In a second step, which was added in preparation for this paper, a complete subset of publications was analysed in order to discover how collaborations are depicted in formal communication. Thus we look first from collaborations to rewards and then from rewards to collaborations.

How were observed collaborations rewarded? For all collaborations described in the interviews with scientists from one CRC, I checked if they appeared as co-authorships, as acknowledgements in SCI journals or as acknowledgements in PhD theses written within the CRC (see Table 1).

With three exceptions, all DOLs were rewarded with a co-authorship. One of the exceptions is due to a collaboration that failed, that is to say did not lead to publishable results. Since the other two collaborations had just begun at the time of the interview, and since they have not been rewarded otherwise, it is likely that they failed too. Though this question cannot be answered, there is nevertheless a strong relationship between a DOL and a reward by co-authorship. SERs were relatively seldom awarded by a co-authorship. For ARE and TKH no co-authorships were granted. A certain number of the collaborations were acknowledged either in the PhD thesis or in the publications. However, it is important to notice that about half of the collaborations were not rewarded at all — neither by co-authorship nor by an acknowledgement. There seems to be a considerable proportion of collaborations that is invisible in formal communication.

Table 1. Rewards of the collaborations between research groups within the CRC network (except MUS and TRA)

Type of collaboration	Number	Co-authorship	Acknowledgements in PhD theses	Acknowledgements in SCI journals	Without reward
Collaboration involving a division of labour	35	32	12	0	3
Service collaboration	31	3	5	4	19
Provision of access to research equipment	23	0	4	3	20
Transmission of know-how	32	0	7	0	25
Total	**121**	**35**	**28**	**7**	**67**

What picture of collaboration is produced by formal communication? The starting point for the reverse perspective (from publications to collaborations) is reward by means of co-authorships and acknowledgements. In all, 133 publications written by a total of 567 co-authors were analysed. Of these publications, 91 (68%) contained an acknowledgement referring to other persons. In these acknowledgements, contributions from a total of 309 persons were accredited. But 50 acknowledged persons were excluded because they were identified as belonging to the technical staff and hence not fit in the definition of collaboration.[7] Thus, about 37% of the collaborators who are visible in publications were rewarded with acknowledgements. In nearly all cases, the descriptions of the content in the acknowledgements allowed me to identify the type of collaboration. For example, 'thanks for critically reading the manuscript' was classified as TRA, 'thanks for helpful discussions' as MUS, and 'for providing us with […] cells' as SER. In 17 cases the classification was ambiguous. Thus, the phrase 'thanks … for the help in the assays' could refer to either SER or TKH. In seven cases the type could not at all be identified because the contribution was described generally as 'help' or 'support'.

The analysed CRC publications show mainly the collaborations within a CRC research group (caused by vertical specialisation) and the collaborations of a CRC group with partners outside the CRC network. Collaboration based on vertical specialisation always resulted in co-authorships; that is, both the junior scientist who conducted the experimental work and the group leader who conducted the conceptual work appeared on the author list. Only a small share of the supporting collaborations (SER, ARE and TKH) of the CRC network was rewarded in the analysed publications.

Table 2 shows the distribution of acknowledgements. DOL was acknowledged only once. The person was thanked for being 'involved in the early stages of the project'. This coincides with the observation that almost all collaborations of this type were acknowledged by a co-authorship. The most frequently acknowledged type is MUS followed by SER. ARE is acknowledged relatively seldom.

The overview of institutional affiliations provided in Table 2 shows that most acknowledgements are paid to group members who interact with the authors on a daily basis. Nevertheless a large amount of collaborations with national and international partners are also acknowledged. A total of 71 acknowledgements was given to 48 scientists from other countries. Of these foreign collaborators, 27 have never become co-authors even though some of them received acknowledgements repeatedly over a lengthy period. Interestingly, the share of service collaborations with international partners is relatively high. In all these cases the partners were acknowledged for providing special biological substances (cells, antibodies, etc.). It can be assumed that the high degree of specialisation in many biological research fields forces scientists to look for the assistance of collaborators abroad.

Table 2. Acknowledgements differentiated according to the partners' contribution (collaboration type) and affiliation

	Total	Intra-group	Intraorganisational	External, national	External, international
Collaboration involving a division of labour	**1**	1	0	0	0
Service collaboration	**72**	41	10	8	13
Provision of access to research equipment	**10**	3	3	3	1
Transmission of know-how	**34**	10	6	9	9
Mutual stimulation	**104**	34	10	20	40
Trusted assessorship	**21**	10	2	1	8
Total	**242**	**99**	**31**	**41**	**71**

Table 3. Co-authorship order in the publications

Co-authorship order	Number of publications
group member(s) – … – group leader(s)	113
group leader(s) – … – group member(s)	7
group leader – … group member(s) … – group leader	2
group member(s) – …. group leader(s) … – group member(s)	2

We must acknowledge that there are many collaborations that are not reflected by formal communication. Moreover, a significant share of what is reflected is 'hidden' in acknowledgements that are not usually analysed

Because information on the content of collaborators' contributions was available from interviews and acknowledgements, author lists could be analysed for connections between types of contributions and co-authorship order. Table 3 shows that a great uniformity exists in this respect.

Nearly all co-authors were ordered in the following way. The first author is the scientist who conducted the experimental work; that is, a doctoral student or a postdoctoral fellow. (This information I gleaned from the interviews and the analysed documents.)

The seven publications with the permuted order are of special interest. In these cases the group leader was first author, while another experimenter was listed last. In two cases the group leader did not change from the experimental role to the conceptual role but assumed both. This seems due to the group's specific content of work (development of research techniques and instruments). That is why no split occurred between the practical and conceptual aspects of work. Moreover, this group was not affected by a rapid change in methods. Furthermore, the group leader had accumulated a large amount of implicit knowledge about the method.

The five remaining publications all belong to different research groups in the field of chemistry. However, the different name ordering seems not to be the result of a field-specific pattern alone, because other publications of these chemical groups fitted the first pattern. Nine publications had to be excluded from the analysis because the first author was an external collaborator (not a member of the CRC), whose role in the research process could not be identified.

In the case of a DOL, usually the scientist who conducted the larger part of the experimental work is the first author, followed by the experimenter of the collaborating group. Both group leaders are last authors on the co-authorship list.

If we sum up the empirical observations, then we must acknowledge that there are many collaborations that are not reflected by formal communication. Moreover, a significant share of what is reflected is 'hidden' in acknowledgements that are not usually analysed.

Causes of variations: rules and practices

After having shown the disparities between the distribution of various collaboration types, on the one hand, and the distribution of rewards, on the other, I will now turn to the reasons for this incongruence. The regular patterns of co-authorships and acknowledgements point to the existence of informal rules that govern the reward system and to the existence of habitualised practices. Both rules and practices relate types of collaboration to types of rewards and thus guarantee that research collaborators do not have to haggle over the distribution of the collaboration's output each time.

The most widespread rule concerns collaborations that are based on the vertical specialisation within research groups; that is, between group members and group leader. In publications of these collaborations' results, both collaborators' contributions are rewarded by inclusion in the author list (see also Edge, 1979, page 106, Subramanyam, 1983, page 34). Generally, the authorship of the first author has been easily agreed to because even in collaborations of more than one experimenter (DOLs) there is a certain asymmetry concerning the load of experimental work. Only in one case did an interviewee report the necessity for an explicit decision to be made about the first author. A similarly clear-cut and unambiguous rule is that DOLs are rewarded with a co-authorship.

Up to this point, the distribution of reward could be ascribed to informal rules. With regard to the other collaboration types, it is not instantly clear whether rewarding is due to informal rules or due to habitualised practices (for acknowledgement behaviour, see also Cronin and Overfelt, 1994, pages 183–184). Empirical investigation has limits here because boundaries between informal rules and habitualised practices are fuzzy.

Co-authorship is also granted for time-consuming SER. However, it is because such contributions always concur with the research goals of the scientist providing the service that they must be rewarded. Otherwise scientists would begin to refuse SERs. Acknowledgements are given for minor service collaborations. We see in the case of service collaborations that there are fuzzy boundaries, and the extent to which SERs are rewarded with co-authorships probably depends on local rules and practices. The rule is not as clear as in the case of DOLs. The only rule for the remaining types that seems to exist is that they are not rewarded with co-authorships. Granting access to research equipment relatively seldom seems to be rewarded at all.

Additional rules concern the order in which the co-authors are listed. First is the scientist who conducted the main experimental work. The last author is the leader of the group or head of the laboratory (see also Stokes and Hartley, 1989, page 105). Between the first and the last author are the names of the collaborators, for whom no rule could be found; their order seems to be arbitrary. The assumption that first authors are generally senior scientists (Russell, 1998, page 123; Melin, 2000, page 33) is not supported by empirical data and seems to be an unwarranted generalisation of social science practice.

The rules that have been discussed so far can be assumed to exist in all scientific communities conducting experimental research in small groups. The additional pattern I found regarding chemical publication suggest that these rules can be overlapped by field-specific rules of the scientific community. Moreover, the informal rules of scientific communities are only one among several influences. For example, editors of some journals have established formal rules for authorship. These rules define which collaborative contribution may be honoured by a co-authorship. In fields such as medical research, honorary authorships (named persons with a slight or no contribution) seem to be a serious problem. Therefore editors have formulated stronger rules in recent years (ICMJE, 1997; Pontille, 2000).

Informal rules of scientific communities are also overlapped by local rules. These can be either informal or formalised. For example, there seems to be a local rule (or practice) that allows the conditions for granting co-authorships to members of the same research group to be relaxed. The collaborations within a CRC research group were not systematically investigated because it was not the main subject of my study. However, from the (non-systematic) interview information it can be tentatively assumed that there is a considerable part of service collaboration within the group, which was usually rewarded with a co-authorship. In many research organisations an informal rule exists that requires that the name of the head of the laboratory be added. This would be in accordance with the scientific community's rule if that person contributed conceptual-theoretical work. However, since the head of a laboratory cannot contribute such work to all research processes in a large laboratory, contradictions emerge. Heads of laboratories are granted co-authorships although they might only comment on manuscripts as trusted assessor or do not even know the publications. In these cases, co-authorship is grounded purely on local power, an effect that contradicts the scientific community's informal rules.

All these rules shape — and at the same time are modified by — local reward practices. The following example describes a local reward practice within an extra-university research institute:

> B is listed in most publications, contributes marginal notes. Recently he has said he only wants to be a co-author of G's publications if he has contributed an idea. He does not want to be a co-author because he is head of department, but only if he has been definitely involved. This means he was naturally involved with my design because, well, it was the first publication about this device and the basic idea … stems from him … For the second publication he is a co-author. He said it was not imperative that he be listed as a co-author because he thought he had not made any contribution.

The informal rule was to include the head of the department; this was also the local practice of the research group. Then the local practice was changed because the head of the department observed that the number of research processes in his department to which he had made no contribution had grown. Therefore, he was not interested in being a co-author of all papers. Local practices also differ in respect of which of the group members, in addition to the group leader and the main experimenter, is rewarded and in which form.

> Interviewer: 'Who else is on the list?'
>
> A first author: 'Too many people. There's also G, who was writing her diploma thesis and did part of the statistics, conducted some measurements and so on, she was a biologist. And then there's P, who prepares cells. Then A and D [the group leaders]. And at the last minute A added a name I don't know, W, who was said to have contributed something to the culture of this triple mutant.'

Furthermore, co-authorship is a matter of negotiation of the scientists' interests (see also Subramanyam, 1983, page 36).

> He's also on the list in my second paper … he asked me during a conference, whether he could be included on it since he had also constructed such a device. I said: 'I don't care, I'll add your name.'

Summary and conclusions

Experimental research in the sciences is partly shaped by a vertical specialisation leading to a division of labour between the group leader's theoretical and strategic activities, on the one hand, and the group members' experimental activities, on the

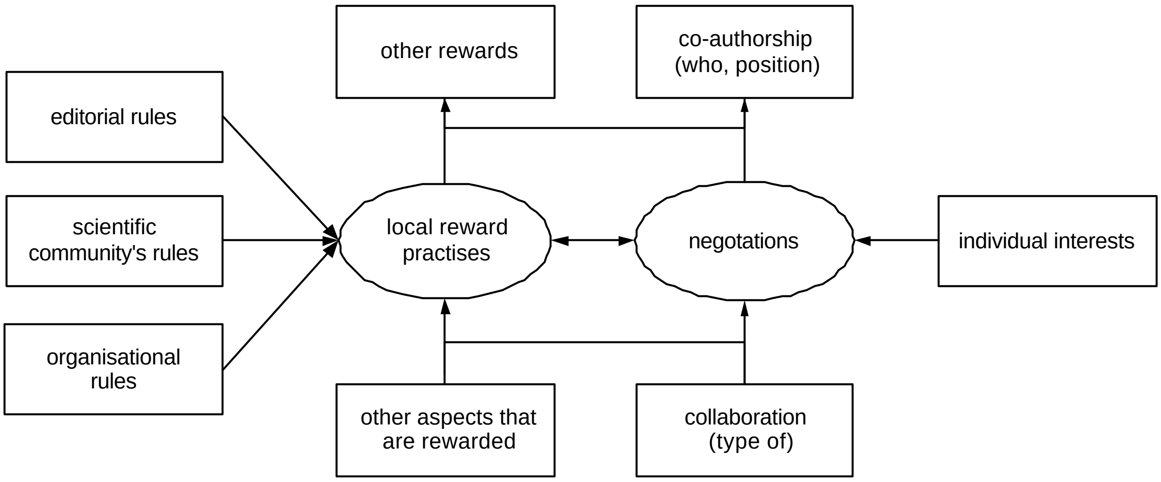

Figure 3. Factors influencing the rewarding of a collaboration

other. As a rule, both activities are rewarded with a place in a publication's list of authors. Here, the group member who conducted the main experimental work becomes first author and the group leader becomes last author. Based upon an extensive qualitative investigation, six types of collaboration classified according to the content of the collaborators' contribution could be identified: collaboration involving a division of labour, service collaboration, provision of access to research equipment, transmission of know-how, mutual stimulation and trusted assessorship.

Depending on the type of their contribution, a collaborator is rewarded with a co-authorship or with an acknowledgement or with nothing at all. As a rule, collaborations involving a division of labour lead to co-authorship. This is the only case besides vertical specialisation where a strong relationship between contribution and reward was observed. For other types of collaborations no clear rules exist. Which contribution is rewarded in which way depends on many local and global influences (see Figure 3). One factor is the type of collaboration. Certain rules of the scientific community exist that operate according to the collaboration type. Additionally, local rules of the research organisation and of the journals' editors influence the rewarding. There is also the researcher with their individual interests. Both the rules and the individual interests encounter local reward practices and they underlie negotiations. As a result, a co-authorship or other rewards are given.

It was observed that about half of the collaborations are invisible in formal communication channels because they are not rewarded at all. About one third of the collaborators whose contributions are rewarded do not appear in co-author lists but only in acknowledgements. The large number of acknowledgements is in accordance with other findings that indicate an increasing frequency of acknowledgements (Cronin, 2001, page 427). The empirical results clearly contradict the findings reported by Melin and Persson (1996) (see introductory section).

The results can be generalized to experimental research in the natural sciences, undertaken in small groups. Collaborative research in large groups — for example, in high-energy physics — is obviously different with regard to both collaborative practices and co-authorships. Because this study is a qualitative one, generalisation follows a different pattern here (Gläser and Laudel, 2002). The investigated sample is not statistically representative for a population and does not enable conclusions to be drawn by inferential statistics. However, since empirical findings show patterns of causation, the scope of findings can be associated with the scope of conditions under which the observed phenomena occur.

What methodological conclusions can be drawn from these results? Of all the collaborations, those involving a division of labour have the greatest number of conditions to be met. They are special in that they include creative contributions from both partners. That is why they can be assumed to be the most important type of collaboration. Fortunately, this type can be measured quite accurately by co-authorships. However, we have to be very careful with the attribute 'important' because it becomes problematic once 'difficult' or 'demanding' are equated with 'important'. Mutual stimulation, for example, needs very few conditions to be met: the partner needs to be interested in the problem and willing to communicate. The importance of such an 'easy' collaboration is emphasised by Subramanyam (1983, page 35):

> For example, a brilliant suggestion made by a scientist during casual conversation may be more valuable in shaping the course and outcome of a research project than weeks of labour-intensive activity of a collaborating scientist in the laboratory.

Collaborations in the form of provision of access to research equipment are often used to validate data by other methods or to test new methods. By combining one's research problem with new methods, interdisciplinarity is promoted. The role of service collaborations is similar; scientists obtain substances for testing methods or data for validation of their results. Many studies have shown the importance of tacit knowledge (e.g. Edge, 1979; Collins, 1982). Transmission of know-how fulfils this function.

Thus, the other collaboration types fulfil at least three important functions:

- they solve technical problems; they stimulate creativity within the research process; and
- they cross boundaries between fields.

These collaborations are measured poorly by formal communication. Thus, as long as we are not acquainted with the correlations between collaborations involving a division of labour and other types, we can make no inference from the measured collaborations to the other types. Under these conditions, one needs to be aware that about half of the collaborative research practice is hidden from the classical bibliometric indicator that is currently applied to measure research collaboration.

Contributors' institutional affiliations do not seem to influence rewarding practices except that intra-organisational collaborations are either seldom or significantly less often rewarded. Therefore, comparisons between national and international collaborations seem not to be biased by the indicator co-authorship.

Notes

1. 'Collaborative Research Centres' are networks of research groups that receive additional funding for pursuing a collaborative research programme. The Deutsche Forschungsgemeinschaft, Germany's most important funding agency for university research projects, finances the funding programme. Its aim is to overcome the hindering effects of university structures on interdisciplinary collaborations. A CRC consists of about 10 to 20 research groups mainly from universities; a few groups from non-university research institutes may be included. All research groups must be located in the same city. They apply for a CRC funding for an initial three-year period with the option of prolonging the funding up to four more three-year periods, each prolongation depending on passing a peer review evaluation. Initial and subsequent evaluations consider quality, thematic coherence of both the network and the programme and planned as well as realised collaborations. Funding for each period is between about 1.5 and 5 million Euro. For further information, see <http://www.dfg.de/english/funding/sfb/sfb_english.html>
2. Any information about the CRCs that is more specific must be omitted from this article in order to protect the interviewee's privacy. Otherwise, a comparison of this article with earlier publications would enable identification of the CRC and, consequently, at least some of the interviewees.
3. There might be other scientists in a group that conduct theoretical-conceptual work. The contributions of postdocs are especially difficult to judge because they are usually in a transition stage between purely experimental and purely theoretical work.
4. Because of the specialisation and the size of the research groups under investigation, two research groups were involved in all observed cases of DOL. DOL can, however, occur within one group if scientists with different expertise work in the same group.
5. It is important to keep in mind here that this collaboration network depicts only a part of the groups' activities, namely the part that involves collaborations within the CRC. Thus, research groups that are connected exclusively by supporting collaborations can be assumed to pursue their main research interests alone or in collaborations outside the CRC.
6. The CRCs showed only small differences in their collaboration density (number of collaborations per research group) and in the distribution of the collaboration types, and no differences in collaborative practices. Therefore only one CRC was selected for an in-depth analysis.
7. To identify technicians, several indicators were combined. First, the work of technicians was referred to in acknowledgements by specific phrases such as 'excellent technical assistance'. A second indicator was the absence of academic titles such as 'Dr' or 'Professor'. Third, information obtained from interviews and observations as well as from an Internet search was used to clarify the status of the person in question. Finally, the SCI was searched for a ten-year time span around the year of the publication containing the acknowledgement. Persons who were not recognised as being the authors of any publication covered by the SCI were likely to be technicians.

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