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# Effects of resource concentration on research performance

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**Abstract.** This paper reports the results of a study commissioned by the Australian National Board of Employment, Education and Training, which examines in detail the effect of resource concentration on research performance, and the basis for critical mass, economies of scale, critical time and risk strategy hypotheses. The widespread introduction of policies of resource concentration around the world are found to have been based on little examined assumptions, and in operation to be at times counter-productive. In general relationships between group size and productivity are found to be linear, though there does appear to be evidence for an optimal size of 5–8. Detailed results and policy implications of these findings are presented.[1]

## The policy context of resource concentration

There is one general principle that is often involved in the restructuring of research – the principle of *concentration*. . . . there is a widespread opinion amongst policy-makers that 'concentration' is a good thing in itself, with many desirable effects on research inputs and outputs. The opinion is usually expressed through the notion that there is a minimum 'critical mass' for internationally competitive research, and hence that entities below that size are non-viable and should be deliberately eliminated from the system (Ziman 1989, p. 22).

In most industrial countries around the world, there has been a growing emphasis on the need to construct more explicit and deliberate policies for science. There are various reasons for this including the escalating costs of many areas of research, growing constraints on government spending, and political demands for greater accountability for all areas of public expenditure. The ultimate aim of these science policies has been to ensure that the limited resources which are available are used as effectively as possible. From this stems an interest in research performance, especially of groups of scientists, be they constituted in university departments, laboratories or entire institutes.

Evaluations of research performance, whether informal or formal, inevitably conclude that some scientific groups are more productive than others. This immediately raises the question of what accounts for performance differences. A wide range of possible determinants of group research performance have been proposed. These include the size of the groups, whether the research is closely linked to teaching, and the type of funding. However, as we shall see, the evidence that these are important determinants of research performance is extremely limited and, where it exists, is often very ambiguous.

A prominent feature of research support policy in many, though not all countries[1]

1. This paper is based on a report prepared by Johnston et al. (1994)

over the last twenty years has been the espousal and implementation of resource allocation processes that provide 'selectivity and concentration'. Implicit in these policies has been the assumption that 'bigger is better'; in other words, that scientific research benefits from economies of scale. This approach has been most pronounced in the UK and to some extent other Anglo-Saxon derivative countries, but it has been the subject of consideration and experiment in many other countries as well.

Thus,

> Science and technology policies at national and international levels have been increasingly impacting on research conducted in universities not only through levels of funding and greater prioritising, but also through influence on the actual structure of research units (OECD 1991).

One of the earliest expressions of the policy of selectivity and concentration was by the UK Science Research Council in 1970:

> The Council is convinced that it must make its support of research, whether pure or applied, more selective, both in relation to particular fields of science meriting concentrated attention and in the choice of scientists responsible and the laboratories where they work. . . . Given its limited resources, the Council must, in order to sustain viable research groups endowed with adequate equipment and ancillary staff of appropriate expertise, concentrate its support in any one field at a limited number of universities (SRC 1970).

Indeed, as discussed in the next section, the UK has substantially pioneered the development and application of 'selectivity and concentration'.

There are a number of other policy, or perhaps political, contexts for the issue of resource concentration in research funding, beyond the apparently simple objective of directly increasing research productivity.

One of these is primarily associated with issues of *efficiency in the management of resource allocation* by research funding agencies. The growth of competitive research funding agencies and processes, and the growth of competition for the funds they distribute, combined with the more general pressure for increased efficiencies in public sector operations, have combined to raise the 'base-unit' of resource allocation which it is efficient to process through the lengthy peer-review evaluation procedures.

At the US National Science Foundation, the sheer scale of the operation has led to a steadily increasing 'minimum level' of grant allocation. The Australian Research Council has found it necessary to establish a 'small grants scheme', whereby a sum of money related to performance in the larger competitive grant scheme is allocated to each university for distribution to its staff on a competitive basis. This is a process of *resource concentration for administrative efficiency.*

Another context of research resource concentration might be termed *resource concentration for political visibility.* Professor Harold Newby (1992), Chairman of the UK Economic and Social Research Council, has emphasised the value to the long-term political and public standing of a research funding agency which can arise from its ability to visibly marshal and direct sufficient of its resources to addressing a significant public issue. In simple terms, continued and future budget allocations to a research funding agency can be shaped by its ability to respond, and occasionally contribute, to a matter of public import.

## The trend to collective modes of research

The shift from individual to group research is a characteristic feature of twentieth-century science (Etzkowitz 1992, p. 28).

The shift towards collective modes of research and arguments of selectivity and concentration are generally associated with the emergence of industrialised (Ziman 1987a) or investment-oriented (Johnston 1991) research.

However, the basis for the trend towards a collective mode of research can be traced to patterns which have a much longer origin. Beaver and Rosen (1979) see the growth of scientific collaboration as a response to the professionalisation of science:

During the twentieth century, the increasing propensity of scientists to collaborate has been a significant trend within the overall pattern of a mushrooming scientific establishment. The marked increase in the growth of collaboration during the past decades is intimately associated with changes in scientific organisation which account for the amazing growth of science. But both collaboration and these changes in scientific organisation have their roots in the professionalisation of science . . . this expansion has led to and indeed necessitated new changes in scientific organisation, such as deepening specialisation and the invisible college. Collaboration offers a way for individual scientists to increase their mobility within a growing array of sub-communities (Beaver and Rosen 1979, p. 243).

Geiger has argued that the decisive factor in the post-war expansion of the US university research system, and its international pre-eminence, was the establishment of organised research and units to pursue it:

Organised research has fulfilled in an effective manner the critical function of mediating between the knowledge demands of society and the knowledge-producing capabilities of university research performance . . . the development of American research universities has depended critically upon their capacity to add, expand, or terminate organised research units (ORUs) in a highly flexible manner as adjuncts to their basic instructional mission . . . . ORUs exist to do what departments cannot do: to operate in interdisciplinary applied or capital-intensive areas in response to social demands for new knowledge (Geiger 1990, pp. 16–17).

However, it is the transformation of research into what Ziman has called a 'dynamic steady state' over the past twenty years that has provided the great impetus towards a collective mode of the operation of research. This is driven by long-term forces historically associated with scientific and technological progress. These include:

- the ever-increasing complexity and cost of research techniques, apparatus and infrastructures;
- the expanding demand for interdisciplinary research on problems of national concern;
- the widening horizons for the practical exploitation of research results;
- the entry into world science of a larger number of nations – e.g. Japan – and the growing influence of transnational factors in national science policies (Ziman 1987b, p. 3).

Under steady state conditions:

Resources are allocated to various fields according to more utilitarian criteria, and competing research programs have to be evaluated more rigorously for both their potential exploitability and their scientific merit . . . enforced institutional selectivity and specialisation has become necessary to provide the increasing 'critical mass' of effort needed to remain competitive in any field of research . . . the collegial organisation of universities is giving way to more hierarchical managerial structures (Ziman 1987b, p. 3).

Ziman thus concluded in 1987 that it is the dynamic and growth of the research system itself which has created strong pressures for the aggregation of researchers into larger establishments:

A 'critical mass' of people and instruments is thus needed, whether for a team undertaking a single large project or in a research group carrying out a program of coordinated projects in the same field. The actual aggregate of resources required for viable research varies considerably from field to field, but even where all that individual researchers need is access to a library or a computer, advantages are seen in bringing them together into specialised groups. The intellectual environment in such a 'centre of excellence' is more stimulating both for mature scientists and for graduate students requiring a thorough training in research skills (Ziman 1987b, p. 11).

It is of interest to note that three years later, Ziman was more qualified in his articulation of the benefits of policies of selectivity and concentration:

The arguments favouring the concept of 'critical mass' for scientific excellence are . . . far from conclusive. There are some particular reasons for concentrating resources and effort, but they do not hold in general (Ziman 1989, p. 24).

Lowe (1991) went as far as to refer to 'the widespread superstition that the achievement of a critical mass is necessary for high-quality research'. He identified four problems:

The first two arise from the fact that the concentration of resources has negative effects as well as positive ones. Putting the best researchers in charge of centres turns them into research managers. . . . Secondly, it is necessary to take account of what economists call opportunity costs. . . . The third problem is that the establishment of centres or specialised research institutes create units which tend to be self-perpetuating, thereby reducing the capacity of the research funding system to respond flexibly to changing priorities. . . . Finally, it is in the nature of the process for establishing such centres that they tend to perpetuate the traditional division of academic research into the established disciplines (Lowe 1991, p. 187).

## The concept of the research group

One of the major weaknesses in the studies cited in the previous section is in their consideration of the concept of the research collectivity or group. By and large the group is considered as essentially unproblematic – a simple collection of researchers, with some hierarchy of leaders, colleagues, post-doctoral fellows, research students and technical support staff.

However such an approach fails to take into account two important issues. First that research groups are not necessarily homogeneous. Different groups may be organised in different ways according to the technical demands of the research.

For example, the sequencing of a gene, or synthesising a major compound, with the technology available, can be differentiated into a number of separate tasks, using an industrial workflow model, to speed the achievement of the desired objective. Alternatively a particular project may require specialist inputs from a variety of different specialists. Such a task and functional division of labour is quite different from a collegiate group pooling their expertise to work on a challenging multi-disciplinary problem. Groups may also be organised and operate differently according to the management style and objectives of the leaders.

The second issue is that groups are more than simply a collection of individuals, even with some acknowledged difference in status. There is almost no consideration of the dynamics of groups themselves, apart from their direct contribution to research performance through access to equipment, knowledge, and communication.

There is a considerable literature in the fields of psychology and to a lesser extent management which is relevant to this issue. Thus Steiner (1966) argues that the productivity of a group may be conceived as a function of task demands, resources and process. Frank and Anderson (1972) tested Steiner's models, and found that increases in group size enhanced quantitative performance on disjunctive tasks.[2]

Brooks (1982), in an analysis of software development, demonstrated the relationship between output and group size depends critically on the nature of the task. If the task is perfectly partitionable, increased size will increase output. However increased size introduces significant communication and training costs. In a task with complex inter-relationships, increased group size is likely to lead to decreased output. He concludes that increasing the resources to a creative project which is behind schedule will only put it further behind. Also that the model of the surgical team, where each member has a specialist knowledge and function to support the leader is far more appropriate for creative tasks than division of labour in the assembly line manner.

Platt (1988) draws on the categorisation of Lazarsfeld *et al.* (1972)[3] to examine the UK UGC exercise of selecting outstanding departments for enhanced research funding. She argues that the key measures such as research productivity are methodologically analytical, but have been treated as if they were substantively global. It is not possible to assess whether there is a true substantive effect of the collective on the individual if the data do not allow these effects to be distinguished. She goes on to draw interesting policy implications:

> If, for instance, people in large or small departments do better, is it *because* of their size, or for some other reason which happens to be correlated with size? Where individual characteristics are the prime determinants, the same individuals would do equally well wherever they were located, and so could be redeployed if other reasons made that desirable. Where aggregate collective characteristics are relevant, a prime consideration would be the composition of social units, with implications for unit recruitment policies. Where global collective characteristics are crucial, policy intervention at quite different points would be required. Some global properties are a direct product of institutional policy and decisions: size of department, formal rules, systems of institutional rewards and punishments, and so on (Platt 1988, p. 525).

The characteristics and efficiencies of the research group have recently become the object of scrutiny of a few science policy analysts. The policy arguments about and analysis of selectivity and concentration is commonly presented as a bipolar choice between individual researchers and large hierarchical structures.

There are, however, other models of organisation. In particular, there is some strong analytical support for the view that, at least in the natural sciences and engineering, and often in the social sciences also, it is the small research team, composed of one or two leaders, possibly other colleagues though usually on a temporary basis, post-doctoral fellows and post-graduate students which make up the effective operating unit; the heroic lone researcher has almost mythical status:

> To speak about the individual in the research system is an impossible task. Either this mysterious creature is a mystical being, existing only in nostalgic fairy tales, or it is a statistical aggregate, reflecting after disaggregation positions and other distinctions of stratification in hierarchical structures (Nowotny 1990).

Moreover, there is at least substantial argument that the small research team continues to be highly effective under the conditions of industrialised science. Thus Ziman (1989), in sceptical mood, argues that the principle of concentration:

> is not, however, self-evidently well-founded, nor is it simple and straightforward to apply. For a variety of reasons, a research group below a certain size may be at a severe disadvantage in achieving international recognition in a particular field. . . . But the aggregation of resources, facilities and personnel into larger units is not necessarily the way to achieve these ends. . . . At a certain point the traditional arguments for the *dispersal* of research funding and research leadership must put a limit to the concentration process (Ziman 1989, p. 22).

Etzkowitz (1992) mounts a strong argument for the effectiveness of the small research group. He acknowledges advantages of the large research centre: e.g. the ability to purchase equipment beyond the means of smaller groups, the stability and accumulation of experience which comes with security of position, and the potential richness of information flow and experience exchange.

At the same time, small research groups also have their advantages. They have ready access to their less sophisticated equipment, in contrast to large groups where access to equipment is necessarily controlled by bureaucratic procedures:

> The ability to have access to the tools for 24 hours a day is viewed as a crucial advantage of little science because it allows for rapid alternation between data collection and analysis, in contrast to the *modus operandi* of big science where these are ordinarily carried on in separate stages with perhaps a wait of months before a return to the research site is possible. Constant availability of the tools of research is viewed as a partial recompense for the ability to acquire the latest and most sophisticated equipment (Etzkowitz 1992, p. 29).

The composition of the small research group is highly dynamic, with post-graduate students and post-doctoral fellows using it as a staging post to subsequent career steps, and academic colleagues forming temporary liaisons. While this leads to an enormous investment in training, it also provides for a steady influx of new ideas, and rapid transfer of knowledge to other research sites.

Etzkowitz portrays the move from small research group towards a large research centre as commonly being driven by fairly shrewd judgments of self-interest more than scientific factors:

> There are two strong overt forces leading to the formation of centres. One is the desire to obtain equipment that cannot be acquired with limited funds; the other is the utility of establishing long-term collaboration on a specific project or area of science. Underlying both these forces is the common premise that the association of several prominent investigators under a common banner is more likely to attract large sums than can a single individual. There is also the incentive that participation in a centre, with its capacity to provide longer-term research support to members, could increase the likelihood of continuity (Etzkowitz 1992, p. 45).

Etzkowitz concludes that the large scale scientific and technological projects which represented hitherto the highest accomplishments of the US science system (the Manhattan Project, Apollo, the instruments of particle physics – i.e. the age of the strong program of research resource concentration) may no longer be appropriate. The model of the small inventive high technology firm in Silicon Valley (which had its origins in academic models) may now be appropriate for the organisation of research:

> Research groups of graduate students led by teachers and post-doctoral fellows are the academic analogues of the small firm in high technology industries. . . . These are recognised as the engine of productivity in research and of effective graduate training in American universities. . . . It is as relevant today as when the organisation of doctoral research was a creative response to the financial constraints which utilised the formation of research institutes in the United States, and which gave birth to little science in an earlier area (Etzkowitz 1992, p. 50).

If small research groups are such an effective unit of organisation of the research enterprise, do they have an optimal size? There is an apparent consensus among researchers:

- some empirical evidence suggests that the optimal size of a research group is about six fully qualified scientists working in the same problem area, with perhaps another dozen support staff, graduate students and post-doctoral fellows, not to mention as many foreign visitors as can be accommodated (Ziman 1989, p. 24);
- an academic research group may consist of as few as three persons . . . up to more than twenty. A middle range of four at the lower limit and six to eight persons at the upper limit . . . is viewed as the ideal number (Etzkowitz 1992, p. 36);
- the most appropriate size is about six – larger groups suffer major leadership complications (Hare and Wyatt 1988); and
- the size of the typical European research group is around five (Franklin 1988).

We conclude firstly that the structure, dynamics and performance of the research group across disciplines is a seriously under-researched phenomenon.

Secondly, it is evident that implementation of policies of selectivity and concentration require a much better understanding of the characteristics of research groups that are important in achieving the potential benefits of such a policy.

Thirdly, both policy and analysis need to take greater account of the structural dimension, and the extent to which some mix of large centres, a variety of small research groups, and 'cunning individuals who carve out niches for themselves within the larger research system' (Nowotny 1990) might provide the most productive research system.

## Some findings of this study

This study was based on three components:

- a detailed survey of the world literature, including 'in-house' reports, and of experience with research resource concentration in a wide range of countries;
- a five-year program of research conducted by the Science Policy Research Unit at the University of Sussex on the factors affecting research performance in the UK, with a particular emphasis on departmental size; and
- an exploratory analysis of the evidence for critical mass, economies of scale, 'critical time', and 'risk strategy' effects in the performance of Australian research groups.

Contrary to a widely held assumption that little research has been conducted on the effects of resource concentration on research performance, a comprehensive literature review, strongly assisted by the international science policy research community, revealed an extensive body of literature stretching back over the past twenty years.

The results of this body of work can best be characterised as ambiguous and contradictory. The majority verdict is that research output is linearly related to size with no significant economies of scale apparent. Others have argued that the relationship between output and size is more complicated – for example, that there are economies of scale up to a certain group size after which diseconomies set in. One possible reason for the divergence is that different studies have focused on different units of analysis – research groups, departments or entire institutions.

The principal findings of the UK studies on research performance in departments are:

- Productivity increases slightly with the size of the department in physics and chemistry, although not in earth sciences. However, even in these first two fields the effect is very small, with size explaining only a few per cent of the variation in output. If research students are included in the calculation of department size, or the Oxbridge data are excluded, the correlation between productivity and size disappears.
- Interviews with researchers in mathematics, physics, chemical engineering and biochemistry departments revealed that they consider links with teaching to have a minor influence on research performance, and the effects of department size to be even less important.
- Critical mass effects are regarded as important at the level of the subfield-based group rather than the department. A researcher needs to be a member of a group

of four to six staff (together with perhaps three or four research assistants and Ph.D. students) working together in the same subfield if they are to be able to compete internationally. There are few direct economies of scale from research per se, apart perhaps from in fields like biochemistry where equipment may be shared across subfield-based groups.

- A statistical analysis of size effects in the published output and citation impact of British university departments revealed that for physics and chemical engineering there is no correlation between size-adjusted publication productivity indicators and size – i.e. there is no evidence of economies of scale in these two fields in relation to published output. There are moderate correlations in biochemistry suggesting that there are some benefits to be derived in this field from being located in a larger department, perhaps linked to the sharing of equipment between subfield groups.

The principal findings of the studies of the performance of research groups, which can only be indicative because of the small sample size, are:

- the adoption of a policy of concentration in the UK in research in condensed matter physics produced larger and more experienced groups, but these groups did not appear to perform as well as their US counterparts, where no such policy was employed, because of the unintended consequence of the policy in 'freezing' the chosen UK groups, thus preventing the inflow of young researchers and new ideas;
- In Australia, the results of a preliminary comparison of the performance of Special Research Centres and other research groups in the same field indicated that the SRCs have a significantly higher level of output, and an apparently higher level of impact, but a lower productivity per researcher; however, despite their substantially larger size, the number of authors per paper for the SRCs is the same as that of the other research groups;
- Both Australian and UK studies have provided no evidence that research productivity is seriously impaired by the normal teaching commitments of senior researchers. Researchers moving from a research-only to a teaching and research position do not appear to suffer a decline in research productivity. Nor, in an assessment of factors affecting research performance, is teaching rated as very important.
- Australian researchers, in responding to questions about factors affecting research performance, placed most emphasis on international collaboration, and the 'critical mass' effect. Both of these are related to collective modes of research. The consensus was that a group of somewhere from 4 to 7 (variously defined) was necessary for effective research, but that size alone was not enough.
- A number of responses indicated that linkages into the international community could operate as a substitute for a local group; There was even an indication that the very cost of scientific equipment, which is often cited as the 'standard' argument for concentration, could be having the opposite effect. Because major equipment is only available at international centres, it is access to these centres,

and to the researchers that gather there, that is important, rather than the size of a local group.

- Strong evidence was presented of the way in which the attendant scale and continuity of SRC funding could provide the basis not just for a higher level of research activity, but for research of a different kind, research problems which were more strategically targeted, with a higher risk, but the promise of a greater achievement. Directors adopting these high risk strategies (successfully) were able to point directly to a range of qualitative measures of high international scientific recognition for their achievements.

These findings lead to three major conclusions about the relationship between research performance and resource concentration, which from some perspectives may appear contradictory. They are:

1. *There is a positive critical mass, or threshold effect, in many fields of research in the natural sciences.* Below a certain size, variously estimated at from 3–5 academic researchers plus post-doctoral fellows, post-graduate students and technical staff, research performance is reduced. In general, if research groups grow significantly larger than this size, inefficiencies set in which lead to fission.

   This size represents the mode of research groups. There are, however, exceptions with strong research performance from groups of smaller size, and occasionally individuals.

2. *There are no economies of scale, beyond this threshold effect.* In general productivity increases only linearly with size.

3. *Large, well-funded and well-led research groups produce more publications, of higher impact, and receive much higher international recognition than do smaller groups*, when group output is the basis of comparison.

The significance attributed to the latter findings depends critically on the basis of productivity. The former assumes the normal economic measure of labour productivity per head. The latter rests on the assumption that it is the output of the collectivity which is the most important. There is a range of evidence to suggest that the traditional economic assessment may be less appropriate when applied to research, than the collectivity-based analysis.

In research, the competition is primarily for intellectual achievement and recognition. This competition does not depend directly, or at least as much, on the ratio of outputs to inputs, which is the basis of economic productivity. Rather it is the ability to marshal resources, including intellectual capability, to achieve 'significant advances' ahead of the competition that counts. In this case, group productivity may be far more important than individual productivity. Scientific recognition is based on group output, and the ability to capture significant attention based on quality and quantity of output, rather than output per researcher.

**Policy implications**

A number of policy implications are drawn:

- The evidence for the threshold effect supports the implicit policy of science research funding agencies in favouring proposals from teams of researchers, rather than individuals.
- There is no support for a policy of increasing resource concentration for the purposes of increasing unit research productivity. Nor is resource concentration an appropriate policy objective in itself. However, it may be appropriate for other objectives, including achieving top international recognition for fields of research in Australia.
- Evaluation of the performance of the recipients of concentrated resource support, such as the ARC Special Research Centres, and of the programs responsible, should most appropriately be made by comparison with comparable centres and programs elsewhere (usually overseas), rather than with non-centres in Australia.
- Resource concentration is not an appropriate policy objective in itself. Policy questions such as 'what proportion of ARC funds should be devoted to concentrated forms of support, such as research centres' cannot be resolved by reference to an algorithm of the returns from resource concentration. Rather, a detailed assessment of the precise advantages of resource concentration in the particular context need to be made.
- Assessment of a policy of resource concentration needs to be carried out in the context of the what might be called the different tiers of government support for research in universities, and the relative importance of and balance between these tiers.

  The first of these tiers is concerned with the maintenance of the levels of scholarship and linkages with the international research community, necessary to underpin quality higher education. The resources required at an individual level are generally modest, though collectively, for the whole 'Unified National System', they amount to many millions of dollars.

  The second tier can be considered to be the support of committed, cumulative research programs, of an internationally recognisable quality, with objectives of scientific or technological advance, or application to particular purposes. This activity, largely supported by the ARC, has a different relationship to economic outcome than the first category, and needs to be assessed accordingly to these different standards. It also requires a higher level of funding per researcher.

  The third tier is directed to achieving international leadership in selected research fields, or the development of new technologies of particular promise. These ambitions are much more exposed to the forces of global competition, and hence need to be resourced and managed in a way that provides the basis for international competitiveness.

  There would appear to be a strong case for a much clearer differentiation in policy of the objectives of these three tiers of research activity and support. One advance might be to establish and publicise the level of funding for each of these categories. There is also a need for an improved understanding of the form and extent of synergy between the three types of research activities.

- Some doubt can be cast on the use of performance indicators to evaluate research, at least when applied to relative levels of performance through the 'Harris Points' scheme. While it may be appropriate to, for example, a comparison of discipline performance over a significant time period, the evidence of this study suggests that the scales may be too compressed to adequately distinguish between good quality, international standard research, and leading edge, world-ranked research.
- The research in this project has also served to highlight the limited understanding of factors that may affect research performance. Group size, and access to resources, are only two of these. Longitudinal studies of the formation, growth and decline of research groups across a range of disciplines would be necessary to gain a better understanding of these factors. Equally, the structure, dynamics and performance of research centres is a seriously under-researched issue.

## Notes

1. There appears to be a general, if loose, correlation between the pressure on public funding of research, often related to poor national economic performance, and adoption of policies of selectivity and concentration. A similar relationship has been noted with the introduction of priority setting processes (Johnston 1991).
2. They also came up with the remarkable finding that odd-sized groups were more effective than even-sized groups – a clear guide to research managers!
3. Three different types of properties may be used to characterise collectives: analytical properties based on individual data; structural properties, which are derived from the relations of the group members; and global properties, based on data about the whole group.

## References


Beaver de B., and Rosen R. (1979). 'Studies in scientific collaboration III professionalisation and the natural history of modern scientific co-authorship', *Scientometrics* 1, 230–245.

Etzkowitz, H. (1992). Individual researchers and their research groups, *Minerva* 30, 28–50.

Franklin, M.N. (1988). *The Community of Science in Europe: Preconditions for Research Community Countries.* Sydney: Gower.

Geiger, R.L. (1990). 'Organised research units – their role in the development of university research', *The Journal of Higher Education* 61(1), 1–20.

Hare, P. and Wyatt, G. (1988). Modelling the determination of research output in British universities, *Research Policy* 17, 315–328.

Johnston, R. (1991). *Selection of Basic Research: An International Comparison*, prepared for OTA, US.

Johnston, R., Grigg, L., Currie, J., Martin, B., Hicks, D., and Skeg, J. (1994), 'The Effect of Resource Concentration on Research Performance', AGPS, Canberra.

Lowe, I. (1991). 'Science policy for the future', in Haynes, R. (ed), *High Tech: High Cost?.* Sydney: Pan Macmillan, pp. 177–191.

Newby, H. (1992). New Arrangements for the Organisation and Funding of Research in the UK – an ESRC Perspective.

Nowotny, H. (1990). 'Individual in the research system', in Cozzens, S. *et al.* (eds.), *The Research System in Transition.* Dordrecht, The Netherlands: Kluwer Academic Publishers, p. 340.

OECD (1991). *Science and Technology Policy Outlook.* Paris, OECD.

Platt, J. (1988). 'Research policy in British higher education and its sociological assumptions', *Sociology* 22(4), 513–529.

Science Research Council (1970). *Selectivity and Concentration in Support of Research.* London: SRC.

Steiner, I. (1966). 'Models for inferring relationships between group size and potential group productivity', *Behavioural Sciences* 11, 273–283.

Ziman, J. (1987a). *Everything You Wanted to Know About Nothing.* Cambridge: Cambridge University Press.

Ziman, J. (1987b). *Science in a 'Steady State'.* Science Policy Support Group Concept Paper No. 1, London, SPSG.

Ziman, J. (1989). *Restructuring Academic Science*, Science Policy Support Group, Concept Paper No. 8, London, SPSG.