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Post-genomic science: cross-disciplinary and large-scale collaborative research and its organizational and technological challenges for the scientific research process

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We examine recent developments in cross-disciplinary science and contend that a 'Big Science' approach is increasingly evident in the life sciences—facilitated by a breakdown of the traditional barriers between academic disciplines and the application of technologies across these disciplines. The first fruits of 'Big Biology' are beginning to be seen in, for example, genomics, (bio)-nanotechnology and systems biology. We suggest that this has profound implications for the research process and presents challenges both in technological design, in the provision of infrastructure and training, in the organization of research groups, and in providing suitable research funding mechanisms and reward systems. These challenges need to be addressed if the promise of this approach is to be fully realized. In this paper, we will draw on the work of social scientists to understand how these developments in science and technology relate to organizational culture, organizational change and the context of scientific work. We seek to learn from previous technological developments that seemed to offer similar potential for organizational and social change.

Keywords: systems biology; scientific collaboration; Big Science; Big Biology; organizational culture; technological change

1. Introduction

Over the last two decades, technological innovations have facilitated enormous advances in the scientific research process. Novel techniques have been devised for probing and analysing matter and organisms from the sub-atomic to the astronomical scale, generating data and information on an unprecedented scale. These technological developments in information technology and computational capability have often been driven by the needs of scientific research and continue, against all expectations, to be powered by Moore's law.[1] Driving these developments has been a desire to answer increasingly complex scientific research questions which require expertise from a number of different academic disciplines

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[1] An empirical law suggesting that the power of computers doubles roughly every 18 months.

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resulting in traditional barriers between academic disciplines breaking down as can be seen for example in genomics, (bio-)nanotechnology and systems biology. It is possible to think of this as 'Big Science', a term which has been used to describe large-scale research which is often cross-disciplinary[2] and multinational (Price 1963; Galison 1992; Finholt 2003). Big Science has referred to different types of collaborative science and it has historically been concentrated in physics research and often in research institutions rather than universities (Galison & Hevly 1992). However, we are now at a point in the biological sciences where a Big Science approach can be seen in the growing cross-disciplinary and large-scale research that has characterized recent years so that we can now refer to 'Big Biology' (Hevly 1992, p. 362) as well as Big Science. In this paper, we will draw on a large collaborative e-Science project, the Integrative Biology (IB) project, to discuss the challenges this approach to research reveals for the context in which scientific research is conducted in the UK.

Since the late nineteenth century when the traditional disciplinary boundaries were institutionalized (Kohler 1982), biology has primarily been a discipline of description and classification, with the development of underpinning quantitative (mathematical) descriptions being limited by the sheer complexity of biological systems. This is now changing very rapidly, and with the completion of the sequencing of the human and other genomes over the last 5 years, the primary goal of post-genomic research in the life sciences has now shifted to the *determination of biological function*—how and why do the processes that together constitute a living organism arise from the constituent parts (fundamentally atoms and molecules) that make up that organism? Biology is becoming 'big', indeed, Oliver (2002) suggests that 'the genomic era is also a story of building the infrastructure and management skills necessary to bring big science to biology' (p. 1). These processes are sufficiently complex to require large, often international, and always cross-disciplinary teams if progress is to be made. The prototypical example is the Human Genome Project (HGP). In his covering letter prefacing the Report on the Human Genome Initiative by the US Office of Health and Environmental Research which recommended that the US Department of Energy fund the HGP, Mortimer L. Mendelsohn suggested that:

> Science is poised on the rudimentary edge of being able to read and understand human genes. A concerted, broadly based, scientific effort to provide new methods of sufficient power and scale should transform this activity from an inefficient one-gene-at-a-time, single laboratory effort into a coordinated, worldwide, comprehensive reading of 'the book of man'. The effort will be extraordinary in scope and magnitude, but so will be the benefit to biological understanding, new technology and the diagnosis and treatment of human disease
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> (Tinoco 1987, p. 1).

In the report itself, the committee stated that:

> Creation of these tools will require a broad interdisciplinary research effort that brings together technologies from the fields of biology, computing,

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[2] We use the term cross-disciplinary when referring to research that draws researchers from different disciplinary backgrounds together on one project and we have taken this term from Jeffrey (2003).

> materials science, instrumentation, robotics, physics and chemistry. This special focus on technological development is distinct from the current national effort in human biology and genetics and requires a new initiative (Tinoco 1987).

These predictions were proved to be true over the next 15 years. Total funding for the HGP and related genomics projects is estimated at over \$3bn in the US alone, but the project was a truly global activity, with funding shared among the many disciplines involved to create large, international, cross-disciplinary research collaborations focused on a single goal (Collins *et al.* 2003).

In this paper, we will draw on the work of social scientists to understand how these developments in science and technology relate to ways in which we are currently carrying out scientific research. The initial experiences in setting up the IB project and the lessons learned from determining the issues to be explored have suggested that this approach has profound implications for the entire research process. These issues, which raise challenges in the provision of infrastructure and training, in the organization of research groups, and in the provision of suitable research funding mechanisms and reward systems, also seem related to a series of concerns in the social sciences, most particularly the relationship between technological development, organizational change and social context. We shall draw upon this literature to discuss the notion of organizational culture and academic research work, and the implications of concepts of career and merit for the possibilities offered by the Big Science approach to investigation as well as to consider the impact of technological development on organizational change.

In §2, we describe in greater detail the impact of advanced technologies on biological and medical research, discussing our experience of the IB project. We seek to learn from previous periods where technological developments seemed to offer similar potential for organizational and social change. Understanding where difficulties arose in experiences of technological design and deployment in relation to organizational concerns and practices will inform what may be required for realizing the potential offered by e-Science to create improved forms of scientific research.

2. The impact of new technologies on the life sciences research process

The recent developments in biotechnology, IT infrastructure and computational resources described earlier, have provided a wealth of biological data at all levels of biological organization. At the molecular and cellular levels, the various genome and proteome projects, coupled with advances and innovations in microscopy and biological imaging, have provided descriptions of the constituent parts and basic structures of living organisms of such detail that researchers are now in a position to contemplate tackling the new grand challenge of determining biological function.

As an example of what this means in practice, consider the function of the human heart. The primary function of the heart is to pump blood around the body, and key questions researchers want to answer are: how does this function emerge from the interactions between the molecules that make up the cells and tissues of the heart; and how and why does malfunctioning of the heart arise in the various forms of heart disease? In order to answer these questions fully it is necessary to trace through a bewildering array of complex interacting sub-processes at the molecular, cellular, tissue and organ levels within the body. As described Seemann *et al.* 2006, to consider just the electrical and mechanical activity that leads to the heart's beating mechanism, we must consider regulation at the genetic level of ion concentrations within cardiac cells which in turn ensure that the ion transport mechanisms via the cell membrane proteins within cardiac cells function correctly. This leads eventually to the propagation of an action potential throughout the cardiac muscle fibres, which then contract in the appropriate sequential fashion to give the pumping action. This is just to consider normal physiology, and we have not even mentioned the blood or haemodynamics. If we wish to consider pathophysiology, we will also need to consider the effects of other systems upon the heart (most obviously the heart's own vasculature), and ultimately the effects of drugs and treatment regimes.

If we consider what would be involved in trying to understand this entire process through laboratory experiment alone, we can begin to see why this type of biological research has very rapidly drawn upon, and in turn influenced, the development of techniques and expertise across a range of scientific and mathematical disciplines. After much detailed experiment, a molecular biologist can gain some insight into the genetic pathways involved in such complex processes, and the biochemist might determine the relevant signalling pathway and encompass it within static diagrams, but these descriptions will not result in a full understanding of biological function. For example, there is no inherent 'oscillator' in the heart—the oscillation arises naturally within the sino-atrial node (which acts as the heart's pacemaker) as a result of a complex set of nonlinear biochemical reactions, and is linked to heart cell physiology, and governed by environmental factors controlling the regulation of gene expression within each cell. This is typical of the way higher-level function emerges in biological systems, and means that the reduction of such a system to its constituent parts yields only partial information.

Given the overall complexity of biological systems, this means that the only feasible approach to recreating these dynamic interactions is to develop mathematical and computational models which themselves possess, and hence explain, how the function emerges from these underlying nonlinear interactions (Noble 2002*a*). It follows that an iterative process[3] between experiment and modelling, necessarily facilitated by HPC[4]-enabled simulation, is the only way to provide descriptions of biological processes with the dynamic complexity to yield the required biological function. The ultimate goal is then to develop models which have predictive power—providing virtual cells, tissues, organs and systems that

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[3] One of the key issues in developing mathematical models of biological systems is the determination of realistic parameter values, or ranges of values, for use within those models. This can only be achieved through close collaboration between experimentalist and theoretician: experimental data is collected, a mathematical abstraction is formulated, and suitable parameter values are extracted from the data for use within the model. Typical predictions may then be made based on the model which suggest a new experimental approach, further experiments may be done in an attempt to validate the model, and/or the model may be refined or extended to include novel experimental findings. This is the central research iteration that is allowing the gradual quantification of biological research.

[4] High performance computing.

can be used in the development of novel drugs and treatments, and, ultimately, for patient-specific care regimes. This new approach to the biological research process has been termed 'integrative' or 'complex systems' biology. It is clearly an inherently cross-disciplinary activity, typically involving mathematical modellers, computer scientists and software and medical engineers, as well as scientists drawn from the life sciences disciplines of biology, biochemistry, physiology and medicine. It is Big Science in the sense that there are large teams of people working together in an attempt to solve particular scientific problems, these teams are of necessity international in character and offer a very wide range of expertise.

(*a*) *The UK e-Science Programme and the Integrative Biology project*

The increasing need for the Big Science approach has resulted in funding programmes being put in place across the developed world to embark on building the infrastructure required to support this approach to this type of large-scale, collaborative scientific research. The UK was one of the first countries to implement a national strategy at government level, and a large (£250M) cross-research council programme was initiated in 2002—the UK e-Science Programme—to put in place the necessary computational or 'Grid' infrastructure (Foster *et al.* 2001). The Programme has defined e-Science to be:

> large scale science that will increasingly be carried out through distributed global collaborations enabled by the Internet. Typically, a feature of such collaborative scientific enterprises is that they will require access to very large data collections, very large scale computing resources and high performance visualization back to the individual user scientists.[5]

The underlying architecture that will support this activity has been termed the 'Grid' (by analogy with the electricity grid), in that the aim is to provide:

> an infrastructure that enables flexible, secure, coordinated resource sharing among dynamic collections of individuals, institutions and resources. It is important to recognize that resource in this context includes computational systems and data storage and specialized experimental facilities.[5]

As this research will be carried out through collaborations between scientists across the globe who are disparate in terms of both geography and discipline, a further key goal of this programme is to facilitate the development of Virtual Organizations of researchers who will be able to collaborate through the technological infrastructure as flexibly, quickly and easily as possible. (In our discussion of technologies for workplace collaboration, later, we consider research which looks at the expectations, and the practice, of new technologies on workplace relationships.)

It is immediately apparent that the emerging research area of Systems Biology described earlier resonates with many of the goals of e-Science and thus, it is perhaps not surprising that some of the large-scale projects that have been funded through this programme have aimed to build Grid middleware[6] to support this new activity in biological research. One such project is the e-Science Pilot Project

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[5] See http://www.rcuk.ac.uk/escience/.

[6] Middleware is usually defined as a layer of software or 'glue' between the network and applications, which can be shared by many applications serving various purposes in different environments.

in Integrative Biology (IB), funded by the Engineering and Physical Sciences Research Council (EPSRC) in the second round of e-Science funding. The IB project is an international consortium of seven universities and one research institution with a mix of both theoretical and experimental groups who are collaborating at different levels. These researchers are currently drawn from a very wide range of disciplines (including computer science, mathematics, medical and software engineering, biophysics, biochemistry, physiology, genetics, molecular biology and several areas of clinical medicine). The extent of collaboration varies according to the part of the scientific problem in which members of the consortium have expertise. For example, the developers in the project hold Access Grid meetings once each week to share ideas and report progress, these meetings typically have about 5–15 people attending. A consortium workshop is held annually with everyone involved in the project invited to attend. The previous workshop was attended by 80 people and we envisage more than 100 at the September 2005 meeting.

The primary aim of the IB project is the development of the IT or Grid infrastructure to support the entire research process of integrative systems biology described in §1—from experimentally derived hypotheses, through the model-building process and HPC-enabled simulation, to experimental and simulation data capture, storage and analysis, and on to model validation and the subsequent design of new wet lab and *in silico* experiments. To determine the requirements for this infrastructure, the IB project has chosen to focus its initial efforts on the needs of two clinical areas, cardiovascular disease and cancer, which together account for over 60% of all UK deaths. These two application areas are complementary in terms both of modelling—each involves multi-scale modelling of a complex biological system—and of the required Grid infrastructure. The modelling of the human heart is the ideal test-bed for building such a system since it is in this area of physiology that the integrative approach is most mature, with the seminal paper, in the area of cellular modelling grounded in detailed experimental work, dating back to the early 1960s with the pioneering work of Denis Noble (1962).

Over the intervening decades, an international heart modelling community has built upon these foundations so that it is now possible to simulate both normal and abnormal physiology integrating effects from the molecular to the whole-organ level (Kohl *et al.* 2000; Noble 2002*b*). Cancer modelling has been chosen as the second application area, since, although there is a large cancer modelling community in the UK, there has as yet been no concerted attempt to take an integrative approach. The aim of the IB project is therefore to support this community in its initial attempts at building a comprehensive model of cancer development across multiple spatial and temporal scales.

The primary goal of the IB project, then, is to develop a virtual research environment, based on state-of-the-art Grid technologies. This environment will be used to support very complex and large-scale research activities undertaken by international virtual organizations spread across three continents and drawn from multiple scientific disciplines. In this, it is a typical example of the Big Science research approach. A more detailed outline of the key technological goals of the IB project, together with a typical example of how the system will be used in practice to support the research process, are given elsewhere in this issue (Pitt-Francis *et al.* 2006), and in greater detail in Gavaghan *et al.* (2005). In the following sections, we will focus on the wider implications of this particular approach for the research process as a whole.

(*b*) *Implications for the research process*

The issues raised from the IB project, and the e-Science Programme more generally, also resonate with previous attempts to transform organizational work and practices through technological innovation, most notably those that have both enhanced and attempted to encourage new forms of collaboration and communication. We shall draw upon this literature to discuss the problems that were encountered when the new technology was deployed in organizational contexts and how the utopian visions for the technology often ignored the detailed understandings of organizations and social practices that are fundamental to the widespread acceptance of a new technology. Thus, we intend to detail the challenges that must be overcome to enable the e-Science Programme to develop improved forms of scientific practice. In the following sections, we will draw upon this research to examine the implications of this approach for the ways in which we currently undertake research. We shall examine what is required of an IT infrastructure to support international virtual organizations collaborating across organizational and national boundaries.

3. Technologies for workplace collaboration

A Big Science approach to life sciences research is facilitated by, and in turn shapes, the new technologies developed from the demands of the newly emerging scientific practices, indeed Hevly (1992, p. 360) argues that ‘Big Science is dependent upon technology’. The success of this endeavour therefore relies fundamentally upon collaboration, and the technologies developed to facilitate that collaboration, within local and across global communities of scientists. Though there are specific features of e-Science that have unique properties such as the ability to share vast amounts of data easily through Grid infrastructures, or the possibility for real-time monitoring of global networks of streaming data, many important lessons have been learned from existing research into collaborative work and how to support collaboration through distributed systems that have implications for the emerging research practices and the technology being developed to enable it. One major insight has been research increasing our understanding into the relationship between new technology and organizational change.

The claim that a major technological development will change social and organizational practices and relationships is not new. Early developments in networked applications designed to support and enable new forms of collaboration also offered the potential to bring about organizational change. These technologies promised to transform quite radically how organizations were structured, with revolutionary new business practices and new strategies for workplace collaboration. This vision can be seen most notably with the development of high-speed networking and the Internet; many researchers pointed to the potential of these developments to transform how businesses and organizations were structured, and consequently how the work was organized to achieve various business and organizational concerns (Hiltz & Turoff 1993). By way of example, some researchers argued that these new technologies would allow individuals to cross organizational and international boundaries and thus, less importance would be placed on the physical location of an organization. People would be less tied to the local area where work activities were taking place, because the technology they used enabled them to work remotely. In addition, with the development of systems to support collaborative work, some researchers envisioned that technology would transform organizational boundaries, flattening the structures and separating components in new ways. These visions predicted that the whole nature of organizational life, processes, structures, boundaries and working practices would change dramatically due to the technological advances. It was often viewed that these new forms of work in effect created what was termed a Virtual Organization (Davidow & Malone 1992). The virtual organization fundamentally may be described as one that relies on collaborating multiparty individuals distributed both organizationally and in time and space. Through the technical infrastructure, individuals would be able to share their skills and resources and coordinate their work activities effectively.

It is apparent that the anticipations of the developments in high-speed networking and the applications that made use of them, resonate in the visions promoted for e-Science where, it is suggested, the technology will contribute to the transformation of the very nature of science itself—not only the work, but also the organizational structures in which the work takes place. But when the predictions for these earlier technological advancements to organizational life have been examined more closely, it seems that even after nearly 15 years, the anticipated changes have not yet been realized. In fact research suggests that overall the relationship between technological development and organizational change is not clear. Seely Brown & Duguid (2000) argue that even after the development of such technologies, often the same organizational structures either continue or seem to be strengthened. It is not clear, then, that technology transforms organizations. Understanding organizational change requires detailed understanding of organizational cultures and practices regarding how individuals and organizations collaborate, which we discuss in §3.1 and the context in which they do so which is the focus of §4.

(a) *Computer Supported Cooperative Work—the nature of work*

How people in organizational settings collaborate, coordinate and sequence their work activities is a major concern of a research community known as Computer Supported Cooperative Work (CSCW). This community emerged in the mid-1980s where the development of high-speed networking, networked applications, and infrastructures provided concerns relating to the implications of multiparty, distributed computer users for system design. Many CSCW researchers held quite radical hopes that new technologies such as workflow systems, collaborative virtual environments and media spaces would democratize organizations, enhance collaboration and communication and, most importantly, provide for new forms of collaboration. For example, systems were developed to support group decision-making (Vogel & Nunamaker 1990) in order to enable individuals to participate in organizational decision-making processes who were previously not involved, but now could be, and in their involvement they could circumvent any notions of status through anonymous contributions. Yet, other systems focused on transforming the nature of bureaucratic recording processes of work activities in organizations, through reducing the need for memos or annotations, and even reducing the need for paper. However, once these technologies had been developed and assessments of their use in practice were undertaken, serious problems emerged, some of which remain as challenges for the e-Science Programme today. Further research in CSCW revealed how various assumptions about the nature of organizations and organizational work were embedded in the design of early collaborative systems (Jirotka *et al.* 1992).

Investigations known as Workplace Studies (Luff *et al.* 2000) revealed extremely complex work practices, far beyond the capabilities of the technologies designed to support them. They reveal how participants rely on complex interleaved and interactional practices, with moment-to-moment shifts from individual to collaborative action and from private to public working. Detailed analyses show how shared artefacts can be used for a variety of practices and how participants rely upon colleagues' public use of these shared artefacts as a resource for collaboration. Furthermore, these studies also focus on the production and use of organizational documents and forms; how these documents were read and written interactionally. This research posed serious challenges for CSCW systems by highlighting the gap between the technologies and the socially organized practices underlying collaborative work. Such practices are often viewed as tacit in nature, 'seen but unnoticed' (Suchman 1995, p. 59). Many workplace studies have detailed the importance of tacit knowledge and practices for the elicitation, production and dissemination of collaborative work. An example in the IB context is the sharing of data through advanced visualization software. The interpretation of a dynamic three-dimensional graphical representation of, for example, the electrical activity in the heart is essentially impossible through verbal means, but through shared use of advanced visualization tools are implicitly understood by experienced researchers in the field. Within the IB project, we are working in very close collaboration with these expert users to extend these tools.

The implications of findings from CSCW for the development of advanced technologies for large-scale collaborations have yet to be debated. e-Science systems attempt to support large-scale collaboration (these interactions, for example the use of visualization tools in biological research referred to earlier, are increasingly about supporting real-time distributed collaboration over the output of the scientific work) and data, simulations, models, graphs, global networks of streaming data from environmental sensors to name but a few. We need to understand how to support such interactions over these artefacts and how to represent data collected from one set of scientific studies to be relevant to other scientific domains. Though adopting a Big Science approach may yet transform existing practices in some scientific settings, we will need to understand the details of scientific practices and tacit knowledge in order to inform the design of the advanced technologies that will enable Big Biology to flourish. Within the IB project, there are a wide range of scientists with a vast set of skills and preferences. Different scientists have, for example, preferred visualization packages that have been developed by the groups themselves and from which they are unwilling to depart at present. By working with the research groups, we have understood how tightly coupled their work is with these tools and the extent to which they can rely on them to be effective and efficient in the work they are undertaking. IB solutions therefore have to consider these constraints to ensure that the work of the scientists is not negatively impacted by the use of the IB technology. Our work on the development of a virtual research environment for these scientists will look closely at the day-to-day working practises, including the management of publications, the policies for data management and the way in which these scientists interact. We will also need to understand the institutional contexts in which this work is carried out and it is to this that we now turn.

4. Organizational cultures

Interdisciplinary and international collaborative research is of necessity carried out in different institutional contexts. IB, as mentioned earlier, is a consortium of several different universities and research organizations and in this paper we are interested in the organizational contexts in which this research takes place. We aim to use the concept of ‘organizational culture’ to explore this aspect of Big Science research. Drawing upon methods and techniques from early anthropological studies of foreign, and historically often exotic societies (Malinowski 1922; Evans-Pritchard 1937), social scientists have extended the concept of culture to provide a way of looking into and understanding organizational and social life. Thus, through ethnographic methods and fieldwork observations, social scientists have attempted to describe the practices and values of particular social groups (e.g. Whyte 1955; Becker *et al.* 1961; Davis 1968) and contemporary sociologists have developed their analyses of culture to make sense of the ways in which different organizations function (Moss Kanter 1977; Acker 1992, 1998; Mills & Tancred 1992; Halford *et al.* 1997).

Culture in bureaucratic organizations (such as universities) has not, on the whole, been characterized by the values that, we argue, are conducive to the success of Big Science and of Big Science programmes such as the UK e-Science Programme—such as sharing of research progress and results, cooperation of consortium members and some level of trust between members.[7] For example, at the heart of a broadly defined traditional academic culture is individual merit. There is a career hierarchy which fosters competition between individuals and between universities and it is in the interests of universities to attract the ‘stars’ of the disciplines. Individual academics may often develop a particular area of expertise within the boundaries of a particular discipline and plough this furrow alone most of the time. Clearly, there are opportunities to work with, and communicate research results to, others in a research community.

Fundamentally, though, much contemporary research is organized by, *and rewards given to*, individuals rather than groups of people working together towards a shared goal. This approach to academic life continues to be dominant despite recent developments in cross-disciplinary science and the parallel commercialization of the results of much of this scientific endeavour (Owen-Smith & Powell 2001).

Career progression, and thus financial and other rewards, is achieved by working successfully within this individualist-merit model of research. Scholars (Acker 1990; Franzway 2001) have identified this model as gendered, in that it can discriminate against those individuals with commitments outside of the

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[7] Shrum *et al.* (2001) raise the point that trust is not necessarily part of collaborative research.

organization and since women have traditionally been responsible for the majority of caring commitments and domestic labour (Walzer 1996; Baxter & Western 1998), their progression can be particularly hampered. Researchers draw upon the gendered division of labour which characterizes many organizations to support this view. For example, in universities in the UK it is manifest in the small proportion of senior appointments and professorships held by women[8] (ETAN 1999; MIT 1999; AUT 2004) and the 16% pay gap between women and men (Bett 1999; AUT 2001), or by the gendered division of labour between academic disciplines and between academic positions and supporting positions. A Big Science approach to research can challenge this individualist model which has traditionally characterized universities. It may even be possible to see a decline in gender discrimination within a more cooperative model such as that offered by Big Science which may be particularly relevant in the biological sciences where there are a higher proportion of women researchers than in other scientific disciplines.[9]

Within traditional disciplinary boundaries we foresee analogies to the gender barriers arising since individual disciplines have developed their own research practices over time. At present, individual research groups within a particular organization are still usually based within a particular single-discipline-based department and are usually ‘led’ (within a hierarchical structure) by an individual from that discipline. This often remains the case for research groups undertaking cross-disciplinary research—there are members of the group drawn from several disciplines but the group as a whole belongs to a particular department. Since research is organized and conducted differently using different vocabularies in different disciplines,[10] there are different research ‘cultures’ between disciplines. It is possible that, as with gender, individuals who do not fall into the majority group may face barriers to their full integration into the organization, and may find the organizational (discipline-specific) culture difficult to understand and to deal with. Scholars have identified similar barriers in operation within political parties and legislative assemblies so that women politicians in the UK often find the organizational culture of Westminster and of local government alienating (see Halcli & Reger 1997; Welsh & Halcli 2003; Childs 2004). Further barriers *within* research groups may arise due to the increasingly international composition of those groups.

In terms of collaborative working, the development of the Big Science approach to cross-disciplinary research is challenging the individualist-merit model of academic work and instead requiring that individuals think about scientific problems across disciplinary boundaries, and work with colleagues—on an equal, rather than hierarchical basis—to solve these problems. Scientists are required to think outside the traditional disciplinary boundaries and to make intellectual links between their own area of expertise and that of others. We are not suggesting that this is completely new; however, what is new is the technological capability that can, and does, underpin cross-disciplinary research on a scale hitherto unseen. Because of these technological developments, and the new scientific problems that

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[8] In pre-1992 universities, 13% of professors are women (AUT 2004).

[9] In the USA in 2001, 34% of those in biological and medical sciences were female compared to 14% of those in physical and related sciences (see http://www.nsf.gov/sbe/srs/wmpd/).

[10] As a simple example in chemistry and physics laboratories, the primary meaning of the word ‘cell’ is different from that in biological laboratories.

are driving this agenda, we are already seeing, in e-Science projects such as IB, cross-disciplinary research which is drawing on a much more diverse group of subject areas. We suggest in this paper that this different way of working may result in different values, and therefore different organizational cultures, emerging from universities and research institutions. The traditional career structure which rewards individual merit may have to be re-thought to take account of the different kinds of achievements that active members of cross-disciplinary research groups accomplish. Our preliminary observations from the IB project suggest there is still a wide variability between researchers' willingness to collaborate which does not appear to be well-correlated with the stage of academic career. There is clearly a general awareness amongst this group, however, of the need to achieve a strong publication record within a recognizable (by one's peers) and distinctive research area. Thus, researchers continue to strive for individual merit in a cross-disciplinary research environment, in part, we suggest because of the individual-merit model of academic careers.

At a more macroscopic level, governments and international academic organizations will have to consider the reform of academic funding and reward mechanisms. At present, as outlined earlier, reward systems are embedded within hierarchical organizations in which a very particular career path is mapped out. Despite the existence of a few 'entrepreunarial universities' the majority fall into the 'immovable cathedrals' (Clark 2004, p. 1) category in which responses to change are slow. Accommodating—and sustaining—the research culture in which Big Biology can flourish may therefore be difficult. The international nature of this approach to large-scale research means that it will be necessary to develop systems of reward that do not disadvantage those involved in cross-disciplinary, international and inter-group research. Globalization of our reward systems is required so that we can view the academic research community from a global perspective, and also reward it from such a perspective. Our funding opportunities, in the UK at least, have already begun to take this approach on board and are encouraging cross-disciplinary research. However, some of our other mechanisms are pulling in the opposite direction. The Research Assessment Exercise (RAE) assesses research output within 'units of assessment' which are broadly discipline, and thus department, based. The funding formula encourages departments to develop critical mass within these units of assessment rather than also encouraging it between them. Additionally, departments within a single unit of assessment compete with each other for funding; it is in the interests of departments to have as few other departments as possible being awarded the highest possible grade as the more units of assessment awarded a higher grade, the smaller share of the overall financial pot each department will be given (Besant *et al.* 2003). Thus, prestige gained from the RAE rests on individual, discipline specific research, which may cause difficulties for individuals working in this new research paradigm. This problem is perhaps particularly acute in Big Biology which typically spans not only traditional discipline boundaries, but also the traditional disciplinary groupings of physical sciences, life sciences and clinical sciences.

(*a*) *Educational challenges within higher education organizations*

The new approaches to large-scale cross-disciplinary scientific research also present the academic community with the challenge of providing appropriate training for new researchers and of assuring young researchers that a successful academic career is possible while working within cross-disciplinary research. Historically, the PhD has given students the opportunity to specialize in a particular area and to become an expert in a small part of a particular subject. With cross-disciplinary research and group research expanding, it may be that a different kind of PhD is needed to service this new way of working. In particular, it is becoming increasingly acknowledged that students need to be exposed to, and gain a knowledge of, different scientific disciplines. Over the course of their PhD programme they need to gain an awareness of, and respect for, different disciplinary cultures and to see the possibilities of drawing on different disciplines for further scientific research.

We have argued in this paper that cooperation and communication are at the heart of Big Biology and research training programmes need, therefore, to take this into account. The teaching of a generic first year Research Methods course, aimed at first year postgraduate students from a variety of different scientific disciplines, is one possible way forward. Within such a course, students could be introduced to the research methodologies made use of in different disciplines, as well as being introduced to the philosophical and ethical context in which modern scientific research takes place. Some aspects of this model of PhD training are already in place in the social sciences in the UK, where the Economic and Social Science Research Council fund $1+3$ studentships. In the first year the students complete a Masters degree, but there is also a generic research methods component delivered in departments. In the sciences, there have also been some initial efforts within the UK to address these issues. The EPSRC and the Wellcome Trust, in particular, have focused on the need to encourage cross-disciplinary movement and training. A particularly good example is the funding by EPSRC at universities across the UK of seven Doctoral Training Programmes at the interface between the life sciences and the physical sciences. In the IB project, funding has been provided to allow a cohort of eight PhD students to undertake such training within the Oxford Doctoral Training Programme, with, for the first time in the university, three of the students coming from other higher education institutions. In recognition of the additional training element required to work across disciplinary boundaries, these programmes provide 4 years of funding, and must include at least a 25% element of courses and training. Similar programmes involving laboratory rotations and taught courses elements have been funded in other scientific areas (including EPSRC's Eng. Doc. Scheme, and various Wellcome Trust Programmes).

These, however, are currently small-scale endeavours (thus very sensitive to changes in financial and political climates), and a wider question must be addressed concerning overall organization of scientific training for cross-disciplinary science. Within Europe, this debate is likely to intensify over the next 5 years as the 2010 deadline for the implementation of the Bologna Agreement,[11] which, if implemented fully, will require a complete overhaul of higher education across Europe.

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[11] The Bologna Agreement is a declaration by European ministers of education convened in Bologna on 19 June 1999. It agrees to construct a 'European Higher Education Area' based on fundamental principles of university independence and autonomy to ensure that higher education and research in Europe adapt to the changing needs of society and advances in scientific knowledge.

5. Conclusion

In this paper, we have suggested that contemporary scientific research questions require a complex, technological infrastructure to be answered. The range of expertise that is needed to answer these questions means that a Big Science approach to some aspects of life sciences research is needed and this is characterized by the need for international, cross-disciplinary and large research teams. In order for these large teams to work together successfully we have suggested that a change in organizational cultures may be necessary.

Big Biology (Hevly 1992, p. 362), then, has been the focus of this paper. We have demonstrated that the cross-disciplinary and inter-institutional approach of Big Science is evident within the e-Science community in our example of the IB project. While the approach of Big Science is not new, its application in biology is. Recent developments in biology and the consequent scientific questions being asked require input from mathematicians, computer scientists, engineers, medical scientists in addition to biologists—this raises new challenges to the way in which biological research has traditionally been carried out. The contemporary era of post-genomic science suggests to us that researchers in institutions across the developed world will be increasingly facing the challenges that this approach brings.

The organizational contexts in which this research takes place will need to adapt to ensure that the Big Science approach can flourish. In particular, the individualist-merit model of academic success will need to be adapted so that those working within complex cross-disciplinary projects are not disadvantaged within their institutions. The educational training offered for scientists of the future will also need to move away from the individual PhD project to training which addresses the particular needs of the Big Science approach. Finally, it may be important for the success of the e-Science research agenda to be wary of technologically deterministic views of scientific progress. e-Science research can be used to capture the complexities of the ways in which individual researchers relate to technological developments and how they, in turn, shape these developments.

In terms of future research, we propose that there is a need for more ethnographic fieldwork (e.g. Jeffrey 2003; Hartswood *et al.* 2005) which examines the working practices of these cross-disciplinary teams and investigates the organizational cultures in which they operate—the recently formed Oxford e-Social Science node, funded by the Economic and Social Research Council, may help address some of these issues.[12] We need to know what contextual factors enhance this research paradigm and what may act as a barrier to its function. In the first instance, both organizational and technological factors ought to be considered. From a technological perspective we need to develop and transform current techniques in order to understand how to promote and maintain large-scale global scientific collaboration and how to best develop technologies to support this. As part of this research, we also need to examine how best to involve individuals in the design and development of technologies—we could draw on the area of Participatory Action Research in the social sciences which would involve those working in this area in the design of the research programme

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[12] See http://www.ncess.ac.uk/ for more information on this node.

itself and has the aim of effecting real change in practice. Additionally, we need to examine how technology can help to communicate and represent information produced in one scientific community for use in another.

We conclude by reiterating our claim that an extensive research programme involving the social sciences is required to investigate the organizational, sociological and educational impact of this research paradigm. We would like to ensure that the promise held out by the new Grid technologies, and initiatives such as the UK's e-Science Programme, begin to be fulfilled.

Editors' note

Please see also related communications in this focussed issue by Ribba *et al.* (2006) and Shim *et al.* (2006).

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