Using Domain Analysis and Organisational Theory to Understand E-Science Sustainability

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Abstract. This paper addresses the issue of sustainability for e-science initiatives by describing a novel evaluation methodology: e-science spectroscopy. It explores sustainability in relation to the work organization and disciplinary structures of research communities and illustrates that current usability theory needs to be refined for the specialised needs of e-social science. The exploitation of novel technologies to support e-social science will be a challenging process because of the necessity to synthesize a wide variety of work practices, collaboration structures and institutional arrangements. Domain experts are often unaware of how the ideologies, assumptions and technical language that they use in their day-to-day work shape their perception of what valid science is, how it should be performed, and the way they interact with scientists from other domains. This contributes to the 'not invented here' syndrome that plagues researchers and undermines trust in the use of new technologies that do not fit with existing work practices and incentive systems. This paper contributes towards a better understanding of this process by discussing conceptual frameworks for understanding why science should be seen as a deceptively varied activity: the institutional organization of knowledge into disciplines can mask different research styles, communication patterns and information needs even within disciplinary boundaries.

Introduction: The problem of e-science sustainability

E-science, the use of large scale computing resources such as the grid in a research context, has experienced a period of rapid growth since the implementation of the core e-science programme in the UK. Currently, many e-science projects are large scale initiatives aiming to develop a particular technology for a new user base. Typically, these initiatives centre upon the creation of a software suite to provide new functionality useful to researchers or industry, or to make additional power accessible for previously-established needs. Some projects are aimed at narrow groups of scientists within particular fields, such as RealityGrid, for Condensed matter and materials research. Many, however, have a much wider potential user base, including not just a wider range of scientists and social scientists but also expanding to industry. Examples in the UK and funded by the Engineering and Physical Sciences Research Council (EPSRC) include the MyGrid family of projects developing tools to support the e-scientist, and the GOLD initiative to create and deploy virtual organisations.

It has been acknowledged within the e-science community that while a number of projects have successfully demonstrated grid-based infrastructure and tools as proof of concept much still remains to be done in terms of uptake across research communities. In order to be successful, e-science projects need to pay attention to all aspects of good computing practice including usability, the issue focussed upon here. In computing, the term usability is used to refer to issues surrounding ensuring that software is user-friendly in every possible way. The concept of usability has developed from early basic principles, such as ensuring that users know which buttons to press and what will happen when they press the buttons. Today, usability encompasses a far wider range of considerations related not only to aspects of human computer interaction for the individual user but also the embedding of computing technology in complex social contexts. It is this latter point that has enabled social scientists to play an important part in the development of complex computing technology. For example, whilst a help system may be logical and transparent and pass standard usability tests, a social perspective may show that in reality it is poorly designed for the environment in which it is used: users simply do not behave in ways that the developers expect (Suchman, 1987).

There is already a body of research devoted to e-science usability, including a dedicated EPSRC funding call. Whilst e-science usability naturally tends to focus on the specifics of the system being developed and how to ensure that it provides key functions needed by actual and potential users (e.g., Kalawski & Nee, 2004; Miles, et al., 2005; Schraefel, et al., 2005), the ultimate aim of most e-science software development is to gain a user base *outside* of the original development team, and e-science technology transference is therefore an important problem with some generic features. This is the issue of *sustainability*: producing a working system may be the easy part: getting others to buy in to the concept and become enthusiastic users may be far more difficult, even if it is free.

The UK National Centre for e-Social Science (NCeSS) perceives that potential users of e-social science will fall into three main categories (Halfpenny, 2006): early adopters (current award holders under the e-social science programme); enthusiasts (who will need practical demonstration of the potential benefit of tools in their research area and for whom the new technology fits with existing work practices; and the unengaged (for whom the complexity of e-science infrastructure would be a disincentive and tools would need to be black-boxed and easily usable). This last category of users, which includes the indifferent, sceptical and antagonistic, accounts for by far the largest segment of researchers in the social sciences. The exploitation of new e-science technologies, therefore, is likely to be an extremely difficult process. Particularly as the history of computing is littered with examples of expensive technologies that failed to develop a significant user base. In the case of academic software, this seems to be a particularly severe problem, perhaps partly because of a lack of understanding of structural differences across knowledge domains. Domain experts are often so steeped in their own practices that they are unaware of how the ideologies, assumptions and technical language that they use in their day-to-day work shape their perception of what science is, how it should be performed, and the way in which they interact with scientists from other domains. This may contribute to the ‘not invented here’ syndrome that plagues researchers (Katz, & Allen, 1982). Gaining new users is hence a key aspect of e-science usability. It is crucial that the e-science community identify qualities of successful and not-so-successful initiatives in order to understand what it takes for an innovative technology to become embedded in scientific practice (Hine, 2004).

Current usability theory needs to be refined for the specialised needs of e-science because of the wide variety of work practices and organisational structures within science (Niederee, et al., 2005; Whitley, 2000), and a lack of research into their impacts upon e-science uptake.

Science should not be seen as a single type of activity: even in similar fields scientists can have very different research styles, communication patterns and information needs (Kling & McKim, 2000). It is easy for a developer to unknowingly move from the developer-centred ‘I-methodology’ (Akrich, 1995; Oudshoorn & Pinch, 2003), to a ‘we-methodology’: assuming that other knowledge domains operate similarly and have a similar organisational structure and knowledge-sharing ethics. To illustrate the importance of diverse socio-cultural practices on e-science uptake, one way in which management concerns manifest themselves is in a lack of trust in a new system’s reliability or security, particularly in the context of collaborative working with remote users (Anderson, 2003). Such collaborative working is a key component of future distributed cyberinfrastructures (Newman, et al., 2003) and it is clearly a complex social phenomenon (e.g., Birnholtz, 2004; Fisher & Dourish, 2004). This can cause problems when different knowledge domains interact using e-science software but lack shared paradigms or operate within paradigms that the new systems do not take into account. For example open source software practices are standard in some parts of computer science but unusual in others. Similarly data sharing is common in some areas of science, such as astrophysics, but rare in others, such as experimental pharmaceutical research.

A second issue needing more investigation is the potential mismatch that new e-science technologies can generate between established and effective management styles in some fields (see Whitley, 2000). The introduction of a radical new technology into a field with a dominant set of tightly embedded research methods may well be resisted or create problems for normal working procedures and established organisational structures designed to closely monitor researchers (e.g., professors check postdoctoral researchers’ techniques in detail). In contrast, radical change may be more easily accommodated in fields that have a plurality of research methods with no set hierarchy of techniques, because work organisation is decentralised (Becher, 2001) and subject to local practices new methods can be more easily assimilated with less risk of outcomes being rebutted by leaders in the disciplinary core.

We view the usability challenges to emerge from e-science as neither a singular problem of developing better tools nor of configuring the user more adequately. In contrast, we believe that successful adoption of e-science technology can only be achieved if tool development and adoption co-evolve. There is a need to better understand this process of mutual shaping. This paper addresses this problem by following an analytic perspective of investigating different e-science practices. The aim is to focus on the influence that difference in the socio-cultural organisational and management structures of knowledge domains has on the appropriation of innovative large-scale shared computing technologies. This can lead to new approaches for the design and implementation of e-science projects, sensitive to the needs of future user communities.

Related research

Recent years have seen progress in Human-Computer Interaction (HCI) from a technology-centred perspective (e.g. interface design guidelines) to a wider understanding of usability as an extended process of dialog between designers and users: user-centred design. A complex product is not ‘complete’ until there has been interaction with real users and feedback into the design process (Stewart & Williams, 2005). Moreover, there is now a recognition that new technology adoption is an inherently social process (Pinch, & Bijker, 1984), one that involves management issues as well as the social context of users and designers (Rohracher, 2005). Ethnographic studies significantly help this broader conceptualisation of usability by finding out “what people really need and how it will fit into the dynamics of their lives” (Siegel & Dray, 2005), and hence have been adopted as a HCI tool (Bloomberg, 1995), going one step further than a traditional requirements analysis. Ethnography has also been acknowledged to be appropriate for e-science because of the complex social and environmental constraints operating upon modern scientists (Anderson, 2003; Schraefel, et al., 2004), and was taught in the June 2005 e-science usability workshop (www.nesc.ac.uk/esi/events/542/). Whilst ethnographic methods are clearly suitable for investigating the impact of the cultural practices of knowledge domains and management structures on e-science appropriation, specific theories of difference in the intellectual and social organisation of scientific fields and its relationship to management structures are needed to provide a comparative and explanatory overview.

To this end we introduce domain analysis (Hjørland & Albrechtsen, 1995), an information science theory, as an analytic tool for understanding usability challenges and opportunities to the cross-fertilization of innovative tools across domain boundaries. The set of theoretical tools developed with domain analysis affords a perspective from which to gain insights into how the differences between the practices of scientific fields affect their needs. This approach treats domains as discourse communities or communities of practice (Wenger et al., 1999), rather than focusing on users in a generalized and context independent manner. Domain analysis can make a valuable contribution to e-science usability by enabling designers to understand the key cognitive and social factors that shape research practices across diverse scientific communities, such as research goals, intellectual priorities, interpersonal recognition and trust, coordination styles, and incentive systems, and to predict how these differences may impact upon user requirements and e-science appropriation.

Understanding the multi-faceted nature of research practice is complex and Whitley's (2000) organizational theory of scientific fields and research governance is essential to complement the domain analytic perspective because it integrates both cognitive and social aspects of scientific work. Thus, it contributes to an explanatory framework for systematically comparing the cultural identity of scientific communities, their research objects, problems, goals, techniques, intellectual priorities, significance criteria, and reputations, across diverse knowledge domains. Whitley argues that many of the major differences between fields can be explained in terms of two dimensions of research practice: (1) the degree of mutual dependence between researchers in a field when making competent and significant contributions to the body of knowledge; and (2) the degree of task uncertainty in producing and evaluating knowledge claims. Whitley's theory has previously been successfully used to explain field differences in such things as responses to changing academic environments (Chompalov & Shrum, 1999; Muller-Camen & Salzgeber, 2005) and appropriation of information and communication technologies (Fry & Talja, 2004; Fry, 2006a; Matzat, 2004), but has not yet been applied empirically to technology uptake within the context of e-science, where the notion of practice may need to be reconceptualized. 'Mutual dependence', both between scientists and fields of research, and 'task uncertainty' have an important bearing on the coordination and control of resources and outputs in scientific communities (Fry, 2006b) and therefore may have significant influence on the appropriation of e-science infrastructures and tools across domain boundaries.

E-science usability and sustainability goals

By conceptualising challenges to e-science usability as an issue related to the social and cultural organisation of intellectual fields this research addresses the question of how to exploit e-science tools and infrastructures and support new forms of knowledge production. In particular it focuses on how the cultural identity and research practices of developer and user communities shape the emergence and perception of work representations in specialist intellectual fields. We describe a novel triangulation of cybermetric and ethnographic techniques to investigate patterns of appropriation across knowledge domains and the creation of new areas of intellectual enquiry. The proposed model also addresses the question of which methods and units of analysis are appropriate for evaluating e-science technologies, applications and their impact on research practices. The outcome of applying such a method could be a new model of usability needs for e-science to support a nuanced usability development for different scientific user communities and needs.

We provide a new perspective for user representations in human-computer interaction for e-science by identifying the key aspects of socio-cultural organizational structures that shape diverse research practices across scientific communities. The approach supports both designers and users in developing a reflexive approach to e-science development efforts by building a model of how new, existing, and potential users make meaning out of e-science tools and infrastructures in the context of their domain boundaries. The long term goal is to provide guidelines for future developers to help them improve appropriation beyond the original development group by users from different intellectual traditions. Two closely related research questions underpin the development of this model. *Under which cultural conditions will scientific communities assimilate e-science technologies developed outside of their domain boundaries into their research practices? How, in turn, does the adoption of novel large-scale shared computing influence the research practices and cultural identity of the adoptive community?* Our specific aims in designing a new method are:

- To use a domain analytic approach to develop a deeper understanding of usability issues for e-science that highlights the causes and effects of different user needs in different types of user community.
- To use concepts from domain analysis such as Whitley's (2000) 'mutual dependence' and 'task uncertainty' to understand which organizational factors shape elements of research practice such as problem formulation, research techniques, goal integration, interdependence, trust, outputs and reputational control.
- To use domain analytic concepts in a novel way to assess whether (a) introducing new distributed tools makes changes in task types for researchers that results in an organisational schism between existing work systems and procedures, and (b) how and when the research context of the originators of new technology (e.g., conducting highly novel e-science development) is culturally similar or different to that of future adopters (e.g., applying developed e-science technologies) and thus identifying potential synergies for technology transfer.

An advantage of the above methods are their ability to tease out non-obvious factors affecting the sustainability of e-science systems, such as the necessity to accommodate different task coordination and integration styles, outcomes and incentive systems across knowledge domains. From the Whitley perspective there is an emphasis on the need to engage research managers (e.g. professors) in discussion about appropriate working practices for the new technology, and predicting fields where conflicts about adoption or during use are likely. Of course e-science spectroscopy is not envisaged as a quick fix for this highly complex problem but as a starting point to ensure that the key issues are addressed.

The method: e-science spectroscopy

We coin the phrase e-science spectroscopy to describe our new method, which is described below in this section. It aims to achieve a breakthrough in the understanding of, and creation of recommendations for, e-science usability through its focus on domain and organisational factors affecting the design process and the uptake of new initiatives. e-science spectroscopy addresses the need to develop appropriate methods for understanding diverse research practices by the innovative triangulation of cybermetric approaches with ethnographic techniques, which enables the scaling-up of case-study methods across multiple domains to gain insights into the socio-cultural issues that influence the successful or unsuccessful appropriation of e-science tools and infrastructure. The data gathered must be interpreted within the overall theoretical framework provided by Whitley and domain analysis. We call this e-science spectroscopy, emphasising the importance of a holistic approach that recognises differences at many levels within science.

Identifying actual and potential users

'Engaged users' of e-(social) science projects can be identified by direct means using interviews, surveys or text-mining techniques.

- Asking the project members who their users are.
- Searching the web for project mentions (e.g., Googling the project name).
- Scanning relevant conferences and literature for project mentions.

'Enthusiasts' of e-(social) science projects are defined as those that there is some evidence to believe may benefit from the technology, but do not use it. These researchers can be identified in the following direct ways.

- Asking project members to list potential new users.
- Searching the web for users of the other similar systems.

In addition, new users can also be sought by scientometric and new cybermetric methods.

- Finding sites linking to the project site or competitors.
- Finding sites co-linked with the project site or competitors (sites linked from pages linking to e-science projects).
- Identifying authors citing research of the project group or competitors, and users' co-authors.
- Cybermetric data on network position (e.g. national, international, trans-disciplinary), of the system's developers should be gathered in order to gain preliminary insights into existing and potential future partnerships.

The end result of the cybermetric analysis includes a list of 'enthusiasts' and a list of potential 'enthusiasts' or 'disengaged' users. This list would then need to be filtered manually by the researcher to select *likely* non-users, for instance selecting those that are similar to known engaged users. Note that it would be more problematic to find 'unengaged' users who did not exhibit any interactions with technology in a way that could be traced by cybermetric techniques. A possible solution in this case would be to profile users (e.g., psychologists at UK universities) and then to seek out (e.g. through psychology department staff lists) others fitting the profile that did not appear to use any similar technology.

The cybermetric data above can in many cases be gained directly using internet search engine advanced searches. For example, the links to a web site can be identified using the linkdomian command in Yahoo! or MSN (e.g., the search `linkdomian:wlv.ac.uk` in Yahoo! or MSN returns a list of web pages linking to the Wolverhampton University wlv.ac.uk web site). Colinks (Zuccala, 2006, in press) can be identified by visiting pages that link to an e-science project page and identifying the *other* links on this linking page. In fact there is now a range of free software that can automate this process, which is useful for large web sites with a high number of links to them (e.g. more than 100). Direct links can be extracted by sending automatic repeated queries to search engines through gateways (APIs) built by the owners for this purpose (Mayr and Toques, 2005). In addition there is integrated package LexiURL (http://cybermetrics.wlv.ac.uk/LexiURL) that not only downloads results from commercial search engines but also combines them and produce summary reports of both links to a site and colinks. There is now a long history of using software like this in order to exploit web links as fully as possible (Thelwall, 2005; Thelwall, Vaughan, and Björneborn, 2005).

Data gathering (interviews and ethnographic techniques)

The emergence of e-science presents a new and complex scenario of research practice and scientific governance in which we do not yet fully know what the key issues are: hence ethnography is an appropriate methodology. Participant observation and in-depth interviews should be used for the development team, actual and potential users. Observation is essential because of the importance of domain differences unknown to developers and users. In order to bring a social and organisational perspective to bear, emphasis should be placed on the description of interactions within both physical and distributed workplace settings. Equal importance should be placed on virtual conferences and intranet traffic as on physical meetings and casual communication in informal settings. Following best practice, the activities should be interpreted holistically, irrespective of location or type (Hine, 2000).

The user aspect of each case study should focus on ‘prescriptive representations’ (Suchman, 1987) of work designed into the system (e.g., help menus, user manuals, software capabilities), and how these representations are used in practice. Participant observation should cast light onto aspects of undocumented work practices that are not embodied in these user representations, such as management styles and field-specific activities. The developer aspect of each case study should focus on how user representations emerge and how the domain culture of the development group shapes how and why certain practices and users are legitimised and afforded in the construction of ‘prescriptive representations’ and why others remain tacitly illegitimate. Studies of usability tend to privilege either the context of the developer or the user. We propose that the two world views should be studied in relation to one another and thus introduce a reflexive element of domain culture in order to support the engagement of users outside the original development project with innovative practices and tools.

In the completed project case study ethnographic data gathering and analysis should be combined with the cybermetric data to trace how the system is being appropriated and whether it is diffusing into other knowledge domains. Project members should be interviewed to gain insights into the motivations behind the system design, how and why certain choices were made in the tasks and processes it should support, the form that the systems requirements process took, and the efforts taken to exploit the system.

A type of Hawthorne effect can be an issue: developers and users may change their behaviour in response to being interviewed or observed, and this should be taken into consideration in the analysis of results. We recommend no attempt to be neutral but to actively seek to enlist new users for systems at every opportunity – using this as a method for gathering data on why potential users do or don’t engage with a technology. The “engagement” policy is a necessary one for a successful initiative, in order to gain the trust of project members, and should also give an additional positive outcome for the research if new users are recruited.

By focusing on persistent issues and using Whitley’s theory with domain analysis as an analytical framework, the ethnographic data gathering and analysis can be contained to a volume manageable for comparative case studies within the timeframe. The data gathering and interpretative processes should be documented in sufficient detail to facilitate external scrutiny, i.e. ‘thick description’ (Geertz, 2000). The application of domain analysis to comparative case studies should make a contribution towards a generalisable model of domain factors by allowing uptake and use of e-science infrastructures and tools to be compared along key dimensions of research practice and knowledge production, including plurality in research approaches, centralized or decentralised coordination of work, levels of interpersonal recognition and trust.

Initial analysis and final theory building

The outcome of each case study can be a report on specific problems and success identified, together with contextual information about he original and potential new user groups, including knowledge domains, research style and management structure. These findings should be placed within a Whitley-domain analytic framework. Ultimately, however, the findings from a varied set of case studies should give key insights into current UK e-science users and potential users. The resulting macro-level data could then be triangulated with detailed understanding about the specific socio-technical context of each situation. The final e-science spectroscopy report and guidelines should seek to extend current knowledge and guidelines using the management and domain-specific insights gained during the project.

Based on Whitley's (2000) explication of 'mutual dependence' and 'task uncertainty' we can hypothesize a number of effects on the coordination and control of research within and beyond e-science. Where the degree of 'mutual dependence' is relatively high admissible problems will be highly restricted in type and conception and deviant formulations are likely to be ignored. On the other hand, where the degree of 'mutual dependence' is low there will be uncertainty about intellectual priorities resulting in a diverse range of problems and different views about how they should be best conceived. Correspondingly, research techniques will be standardized and well-established in domains with a relatively high degree of 'mutual dependence' and contributions that do not clearly fit with existing knowledge and do not rely on accepted techniques, methods and materials by specialist colleagues' are unlikely to be incorporated into the accepted body of knowledge, through publication in core journals for example. In domains with a low degree of 'mutual dependence' research techniques will not be standardized, rather they will be highly tacit, personal and fluid, or tied to particular topics and research areas. In such domains, it will not be obvious when particular methods should be used, nor when these have been applied successfully. Furthermore, there will be less reputational control over research strategies and procedures, which may be of particular significance in how and when e-science is appropriated.

Developing indicators for 'mutual dependence' and 'task uncertainty' is one of the challenges in applying Whitley's theory empirically to the uptake of e-science infrastructures and tools. The two concepts are closely interrelated and cannot be measured in absolute terms (Fry, 2006c). We argue, however, that the effect of each of these two dimensions of scientific practice can be differentiated when we observe the specific institutional configurations and situated practices of knowledge domains. Indicators of 'mutual dependence' and 'task uncertainty' are perhaps most visible in the scientific communication system. As Becher (1989, p.77) argues "communication is central to the academic enterprise" weaving together social and intellectual concerns. To this end, cybermetric techniques (including text mining) are particularly relevant to developing an e-science spectroscopy as they will enable the analysis of quantitative indicators and the scaling up of qualitative indicators, identified during the course of ethnographic analysis, that would otherwise be constrained to a specific case-study.

The scientific controversy, traces of which are often represented in domain literature, is a key example of how the domain analytic approach proposed here could be usefully applied to exploring audiences for e-science. Controversies relating to e-science could be traced using linguistic techniques within both traditional and web-based genres of scholarly communication to evaluate levels of agreement or disagreement around the use of a particular infrastructure or tool. Such controversies would be an indicator of 'task uncertainty' as they would reflect either a lack of consensus within a scientific community about the validity of that particular approach in supporting a valid contribution to the body of knowledge or a critical mass of support.

The degree of collaboration between scientists, either within or across domain boundaries, could also be evaluated based on representations of scientific practice. This has been done extensively in the field of scientometrics, whereby co-authorship patterns have been correlated to patterns of collaboration. In the context of Whitley's theory, collaboration would be an indicator of 'mutual dependence' demonstrating the necessity for interdependence between scientists in order to address substantive research questions within a scientific community. 'Mutual dependence' is likely to be greater in areas where there is greater reliance on tools or large-data sets in producing knowledge and establishing reputations. In addition to quantitative indicators such as co-authorship patterns, interdependence can also be evaluated qualitatively by asking perception related questions, such as whether scientists perceive themselves to part of a close-knit or loose-knit research group or network.

Given the sensitive nature of this kind of research, we commend the need to provide guarantees to case study participants that the results should be used to improve future design efforts and should not be used to monitor them or to provide evidence that could be used against them. Thus, individual participants and projects should be anonymised when necessary.

The primary beneficiaries of an e-science spectroscopy investigation should be developers of ongoing and future e-science projects, who should have improved chances of gaining additional users through understanding the key issues and following the guidelines. The secondary beneficiaries, but perhaps the most important ones, should be scientists who are able to use new e-science technology as a result of improved usability considerations. Funding committees should also benefit from an improved ability to evaluate e-science proposals based upon an improved understanding of usability issues.

Summary

E-science spectroscopy is an attempt to develop a method to assess and promote the sustainability of e-science projects by a focus on users and using social science theories of domain analysis and work organisation. The incorporation of cybermetric techniques allows researchers access to gather and analysis data about non-users and potential users. Information about these groups is essential to the long term sustainability of any large scale project. The social science theories will help developers to gain insights into how their projects are perceived by a wide range of different potential users. E-science spectroscopy will help to identify important design issues that may be raised by potential users because of their differing work practices, such as differing needs for privacy, sharing and management supervision. This method represents an opportunity for social scientists to extend their already strong contribution to the computer science research field of human computer interaction.

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