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**Workshop on Science of Science Policy:
Developing our Understanding of Public Investments in Science**

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Abstract

This position paper builds on Ann Carlson’s summary of the results from the Atlanta workshop that has been distributed as *Discussion Questions for GSF Workshop06-12.pdf*. It starts by introducing a technologically very feasible ‘dream tool’ for science policy makers and many other stakeholders interested in more effective knowledge management and utilization. It lays out the rationale and sketches the design of a socio-technical cyberinfrastructure that supports the storage, integration, collective annotation, analysis, modeling, and visual communication/exploration of terabytes and soon petabytes of relevant data. Maps of science are introduced as a means to interlink, make sense, and communicate complex datasets. Models of science are discussed as a way to gain a deeper understanding of the inner workings of science. The paper concludes by suggesting next steps.

Please note that my main expertise is in scholarly knowledge management and the mapping and modeling of science. The approaches suggested/examples used here have been tested in/drawn from this application domain.

The opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or any other U.S. institution.

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1. Introduction – Building a ‘Dream Tool’ for Knowledge Management

“We are not here just to make ourselves rich, famous, or top consumer of the day or decade, or just for the 3 percent living in our part of the world, we are here for all of humanity.”

Buckminster Fuller

Today, humanity's knowledge is stored in an exponentially increasing number of papers, books, emails and in other formats. The number of publications produced is staggering. Some scientific domains produce as many as 40,000 journal papers each month. No man and no machine can process this enormous amount of information and hence most of the knowledge gets reinvented, is duplicated across sciences, or is simply lost forever after a short period of time. There is an urgent need for better tools to keep track of, access, manage, and utilize our collective knowledge and expertise.

Given that the cognitive abilities of one human brain are rather limited compared to the flood of information we are facing, we need to develop tools that effectively augment and interlink brains to each other and to existing data, information, knowledge, service, and compute resources. We need to support a ‘global brain’ [1, 2] of scientists, educators, practitioners, governmental workers, etc. that crosses national and disciplinary boundaries. We should also aim to support a ‘global heart’ – a deep caring for the many challenges our species is facing and a strong, collective interest to address these challenges in a timely fashion.

At a very general level, a ‘dream tool’ for knowledge management would enable its users to gain an overview of all relevant knowledge, to zoom and filter out entities and relationships of interest, and to retrieve details on demand [3]. It would optimally split work among human users with powerful visual processing, pattern matching, and sense making capabilities and computers with their ability to interlink and process petabytes of data. Its interface should be easy to learn, efficient, and aesthetically pleasing. The interface might use Google Earth (<http://earth.google.com>) to overlay scholarly, economic, census and other data on a globe of our Earth. It should also support the selection and interactive exploration of many different views designed for different information needs such as show me all major experts, institutions, regions, nations, funding in a selected research area; pockets of innovation; pathways from ideas to products, etc. (see also Figure 1 and section 4).

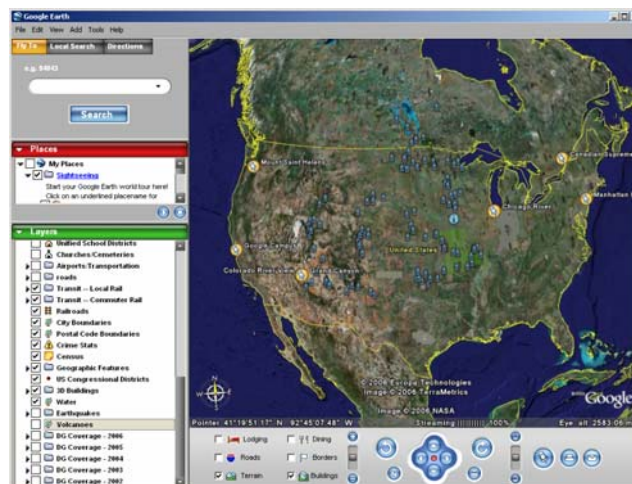


Figure 1. Screenshot of the unmodified interface of the Google Earth browser. Please download from <http://earth.google.com> and enjoy the ease of navigating enormous amounts of data in a spatially explicit manner. Please also become familiar with spatial navigation and the selection of different layers. Imagine the overlay of data that is relevant to the decisions you make. Let me know if such an interface would be useful for you.

The tool can be seen as a ‘macroscope’ that helps us see structure, patterns, trends, outliers in data sets that are too large and complex to be comprehensible to us -- just like microscopes help us to see things that are too small and telescopes are useful when exploring things that are too far away [4].

Note that such a macroscope is not only interesting to science policy makers but also to a number of different stakeholders:

- **Students** can gain an overview of a particular knowledge domain, identify major research areas, experts, institutions, grants, publications, patents, citations, and journals as well as their interconnections, or see the influence of certain theories.
- **Researchers** can monitor and access research results, relevant funding opportunities, potential collaborators inside and outside the fields of inquiry, the dynamics (speed of growth, diversification) of scientific fields, and complementary capabilities.
- **Grant agencies/R&D managers** could use the tool to select reviewers or expert panels, to augment peer-review, to monitor (long-term) money flow and research developments, evaluate funding strategies for different programs, decisions on project durations, and funding patterns, but also to identify the impact of strategic and applied research funding programs.
- **Industry** can use the tool to access scientific results and knowledge carriers, to detect research frontiers, etc. Information on needed technologies could be incorporated into the maps, facilitating ‘industry pulls’ for specific directions of research.
- **Data providers** benefit as the tool provides a unique interfaces to digital libraries.
- Last but not least, an easy interface to mankind’s scholarly knowledge (as ubiquitous as daily weather forecast maps) would dramatically improve the communication of scientific results to the **general public**.

The design of such a tool will require a very close collaboration of data providers, researchers, industry, funding agencies, and tool users. The fact that almost anybody would benefit from this tool makes it much more likely that it can be built.

The remainder of this paper is organized as follows: Section 2 discusses the main features of a cyberinfrastructure that supports the needs discussed above. Section 3 addresses the challenges of data collection, federation, integration, and annotation. Section 4 introduces maps of sciences as a means to communicate the results of data analysis and/or modeling to different stakeholders. Section 5 motivates the design of models of science that help us understand the inner workings of science. Section 6 concludes with a suggestion of next steps.

2. Cyberinfrastructure Needs

The design of a tool/infrastructure that provides access to and helps us utilize mankind’s collective scholarly, technological, economic, etc. knowledge is a non-trivial undertaking. Such an effort is comparable with the design, setup, and maintenance of an extremely good microscope or telescope. It will require major funding – maybe about one tenth of what was spent for the Hubble telescope. Yet, it is money well spent as such a tool/infrastructure will change the way we do science, conduct business, and see our world.

Such a tool/infrastructure needs to provide the storage, services, and computing resources to federate, integrate, analyze, and model a steadily increasing stream of scholarly, economic, census, and other relevant data and to communicate the results. It should also support the formation of communities for means of data annotation (see next section); the development, comparison, and testing of new algorithms; the interpretation of results, etc. Such a socio-technical infrastructure is also called cyberinfrastructure (or e-science in Europe) see the Atkins report on ‘Revolutionizing science and engineering through cyberinfrastructure’ [5].

Many knowledge management tools and some of the first cyberinfrastructures (CIs) were designed in a monolithic fashion making the continuous adaptation of the CI to the changing needs of its users and continuously evolving software and hardware difficult.

A plug-and-play architecture that uses a CIShell like core to plug and play different datasets and algorithms is much easier to evolve and maintain [6]. The CIShell core resembles an ‘empty shell’ that can be filled with datasets and algorithms – just like anybody can contribute and use text stored in Wikipedia (<http://wikipedia.org>). This way different tasks and user groups, e.g., the ones discussed in section 1 can be served.

The integration of a new algorithm into a core such as CIShell is easy. A user simply uploads his/her code and fills out a number of forms and the new algorithm can be selected via the interface. Datasets and their documentation can be uploaded and integrated in a similar way. Hence, the CIShell approach provides a unique bridge between algorithm developers – which might not be computer scientists but biologists, physicists, sociologists, etc. -- and algorithm users. The usage of CIShell can be compared with using a ‘Wiki-Data&Code’ that lets anybody upload and use datasets and software algorithms. Algorithms can be easily compared, combined, replaced, and improved.

CIShell supports the design of server based Web portals and stand alone tools with customized visual or scripting interfaces. Different access rights to datasets and algorithms can be implemented as needed.

3. Data Quality and Coverage

Today, most data needed for a science of science policy, scholarly knowledge management, etc. is vertically locked. That is, datasets are stored in data silos or ‘stove pipes’ that are not interlinked and are not interoperable, see also Figure 2. There exists no database that contains all of mankind’s scholarly knowledge. There is not even a database of all works published in English. The same holds true for other types of data.

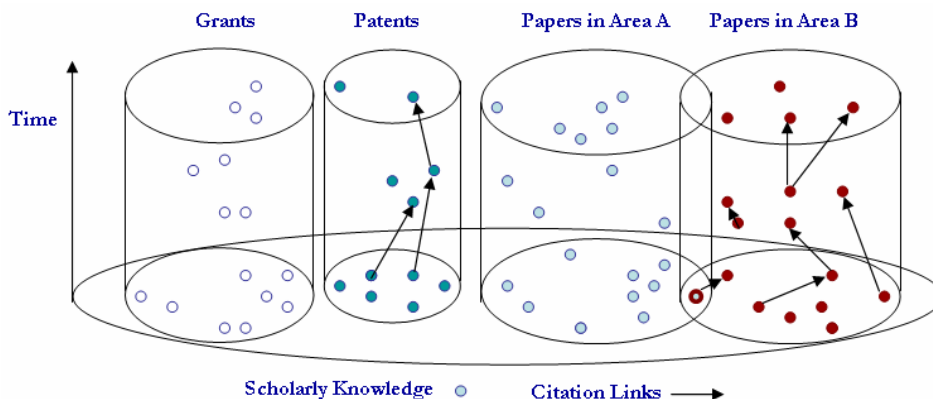


Figure 2: The interoperability and cross linkage problem. Many but not all of today’s scholarly datasets, e.g., papers, patents, grants, are stored and made available so that ‘vertical’ citation linkages can be traversed. There are very few instances in which datasets of different origin and/or type are ‘horizontally’ interlinked.

An ‘interoperability substrate’ needs to be designed (standards might suffice) to ensure that value-adding knowledge management service are not ‘vertically’ locked. Current approaches to overcome this problem are discussed in [7, 8]. Semantic association networks (SNAs) are introduced in [8] as a means to collect, organize, and make sense of scholarly knowledge and expertise in a more comprehensive and timely fashion, see also Figure 3. Among other ends, the proposed SANs facilitate new types of searches, e.g., the retrieval of all authors that worked with dataset x or all papers that used algorithm y ; ease the reuse of datasets and services, thus increasing the reproducibility of results; enable dataset/algorithm/result comparisons at the data/code/implication

level; and exploit data access and data origin logs to indicate the usefulness of resources and the reputation of authors.

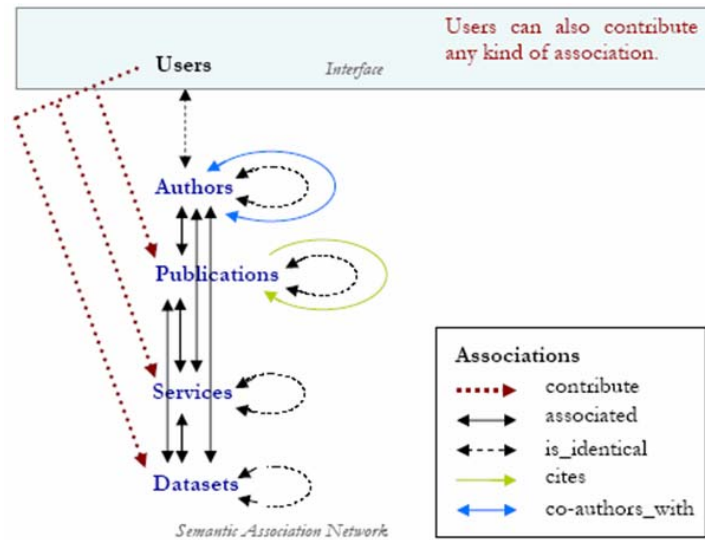


Figure 3: *Semantic Association Networks* interconnect ‘Datasets’, ‘Services’, ‘Publications’, ‘Authors’ and ‘Users’ via diverse associations. Data is provided/contributed by data providers and users. Users are actively involved in the cleaning and rating of the different data types.

If the many different databases can be interlinked then a major data integration challenge needs to be solved. For example, in order to retrieve and analyze all papers, grants, patents, etc. by a certain person/institution/nation the set of unique persons/institutions/nations needs to be computed first. Given different spellings and misspellings of names in different translations this cannot be completely solved by purely automatic means. It appears to be advantageous to combine automatic means with manual efforts that use the ‘wisdom of crowds’ such as WikiAuthors [9].

It might also be beneficial to interlink other efforts such as the Inventables open-source innovation/ creativity effort by companies and amateurs at <http://www.inventables.com>.

The merge of datasets from different cultural worlds – from peer-reviewed literature and hand curated data via open source, wikipedia data to data from Web crawls – will create interesting challenges in terms of data certainty and quality. Data provenance, i.e., keeping a record of where data came from and what was done to it, will be important to evaluate the quality of data that went into a certain analysis and to interpret the results.

4. Mapping Science

Just like old sea charts, maps of science can help people to find places of interest while avoiding monsters. They complement local fact retrieval via search engines by providing global views of large amounts of knowledge.

Quoting from [10]: “Most maps of science have been generated from rather small static data sets (hundreds to thousands of nodes) and for rather limited knowledge domains. Very few studies have undertaken a mapping of the whole of science. Early work on mapping science focused on citation or co-citation linkages between papers. Pioneering examples include the historical map of research in DNA [11] and the mapping of scientific networks [12]. Garfield [13] constructed a map of science based on co-citation linkages associated with 93,800 source documents and 867,600 referenced documents published in 1972. ISI continued studies in this area over the years, the most recent of which shows a map representing the whole of science using the citation linkages of 36,720 documents placed into 35 high level clusters [14]. For a good historical review of the changes in how science has been mapped over the years, see the recent work by Moya-Angón and associates [15].”

Recent work on knowledge domain visualizations [10, 16, 17] attempts to map science on a large scale. The resulting maps aim to equip people with a global view of our collective knowledge and wisdom. Again quoting from [10]: “Our interest in mapping science stems from a desire to understand the inputs, associations, flows, and outputs of the science and technology (S&T) enterprise in a detailed manner that will help us guide that enterprise (or at least that portion of it operating in our institutions) in more fruitful directions. A science map can be an ideal tool for this task if constructed correctly. In the physical world, maps help us to understand our environment – where we are, what is around us, and the relationships between neighboring things. By knowing about our surroundings, we are given more information by which to anticipate changes, especially those initiated in our immediate vicinity. Maps also provide a physical (geographical) structure for comparisons of metrics, such as census figures, vote tabulations, or average temperatures.

To a manager in the S&T enterprise, a science map can provide information in a structured way, provided that the structure is one that is familiar. Semantic maps are not necessarily familiar to the manager, given that they are often organized by concept, and often have a high level of detail. However, a disciplinary map, one in which science is broken up into its component fields, is more often than not familiar given that most corporations and large research laboratories are organized along disciplinary lines, and universities are organized by disciplinary departments. Such maps can be used for metrics that compare institutions or departments, and can also be used to show opportunities and threats.”

A sample science map with overlays of the very complementary funding by the National Science Foundation and the National Institutes of Health is shown in Figure 4.

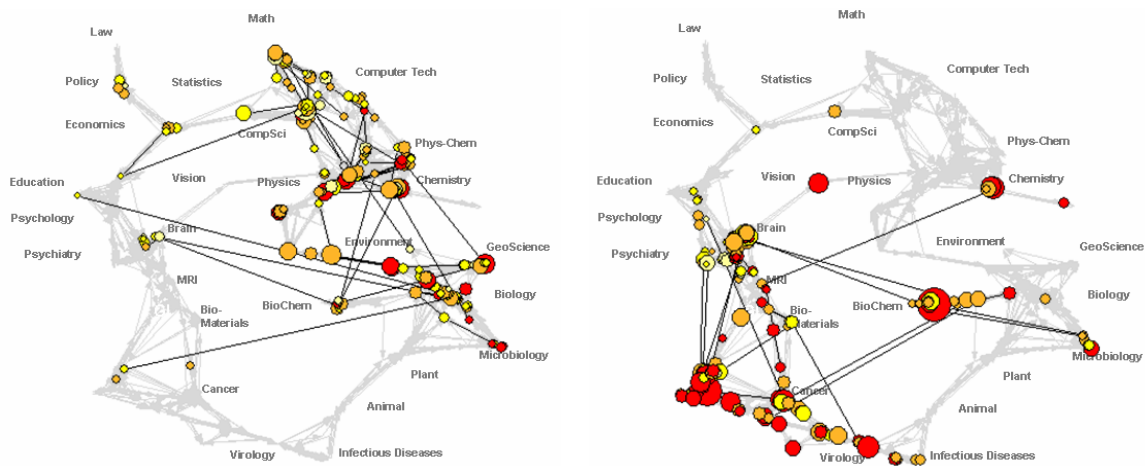


Figure 4: Map of science with overlay of funding by the National Science Foundation (left) and the National Institutes of Health (right). Papers published in 2002 were linked to grants funded in 1999 by common author/principal investigator and institution. Node size corresponds to the numbers of papers while node color indicates scientific vitality, or the speed with which a community of researchers incorporates new ideas.
(Kevin W. Boyack & Richard Klavans, unpublished work)

Many more examples of maps of sciences are showcased in the ‘Places & Spaces: Mapping Science’ exhibit that was designed to introduce maps of science to the general public. The science exhibit is currently on display at the NYPL Science, Industry, and Business Library branch of the New York Public Library in New York City. It is also available online at <http://vw.indiana.edu/places&spaces>. The first iteration (created in 2005) aims to show the power of maps to help us understand, navigate, and manage both physical places and abstract knowledge spaces. The second iteration (created in 2006) aims to inspire discussion about a common reference system for all of mankind’s scientific knowledge. Scientists in many disciplines battled to agree on standardized reference systems such as the electromagnetic spectrum, the periodic table of elements, geographic mappings, and the celestial reference system. These standardized systems are invaluable for indexing, storing, accessing, and managing scientific data efficiently. The third iteration (created in 2007) invites science maps that show not only the structure of science but also its evolution. We

are interested to see what metaphors and design strategies might work best to map the dynamics of our collective knowledge. A total of 10 iterations are planned.

Ultimately, we are interested to serve a ‘science weather forecast’. People might watch it in television (much more interesting than the weather forecast) or online, download it as ‘science awareness’ screen saver (harvesting compute cycles a la seti@home at the same time), or interactively use it via a Web portal interface. The latter interface also supports data input, cleaning, and rating, see section 3. Such a unique interface to our collective knowledge can support many if not all of the needs discussed in section 1. It would give us back a global view of science that Leonardo Da Vinci possessed but nobody has today due to the speed of innovation and scientific progress.

5. Modeling Science

About 40 years ago, Derek J. deSolla Price [12] suggested studying science using the scientific methods of science.

Scientific study also involves the design of (computational) models that aim to capture and reproduce the structure and evolution of scientific disciplines or of all of science. Among others, models support the study/development of

- Dynamic science and technology indicators (emerging research frontiers, evolving networks, trends, feedback loops).
- Evolution of scientific communities/fields. Capacity limit to knowledge/ skills knowable by individual researchers.
- Innovations and their ‘materialization’ in tangible and non-tangible products.
- Interplay of competition and collaboration.
- Evolution of fields – birth, growth, mature, decline.
- Interactions among fields. Optimal interdisciplinary collaborations?
- Comparison of different funding models, e.g., few large vs. many small grants, teach the field how to fish or give them fish?
- Impact of publishing/collaboration/funding mechanisms on the dynamics of fields.
- Interplay of science and laws and regulations, political changes, wars and regional conflicts, natural disasters, and public opinion.
- Diffusion of people, ideas, skills, etc.

The ultimate goal is to learn how to best increase, diffuse, and utilize our collective scholarly knowledge. Quantitative and qualitative data will need to be considered to obtain such an ambitious goal.

6. Suggested Next Steps

The design of the socio-technical cyberinfrastructure and hence the dream tool/resource outlined above is technologically very feasible. Managing the politics, agreeing on standards, finding solutions to copyright and privacy issues, the acquisition of funding, etc. pose major challenges.

A series of meetings in which visions are aligned, data/tool/computing and other resources are pooled, and a master plan of the most useful ‘dream tool’ is drafted might be most productive.

Subsequently, I list efforts in U.S. that aim to increase our understanding of science (policy) and the design of improved knowledge management and science policy tools. The list has no specific order. It is my hope that a more complete list – ideally also comprising non-US efforts and activities - can be compiled in Helsinki.

The National Institutes of Health are interested in the design of better knowledge management tools. On February 6th, 2006 OERRM/OER sponsored "Knowledge in Service to Health: Leveraging Knowledge for Modern Science Management". The symposium explored the field of

Knowledge Management through presentations and demonstrations by experts from academia, industry, and biomedical research funding agencies. <http://grants.nih.gov/grants/KM/OERRM/OER_KM_events> There will be a ‘Think Tank’ meeting on “Science Management Tools” in September 2006. Lead is Israel Lederhendler, NIH/OD <lederhei@od.nih.gov>

The National Science Foundation is preparing a science of science policy call for proposals that will be NSF intends to issue a solicitation inviting proposals. That solicitation is expected to appear during the fall of 2006. Leads are Thomas J. Baerwald <tbaerwal@nsf.gov> and Frank P. Scioli <fscioli@nsf.gov> both Directorate for Social, Behavioral, and Economic Sciences, National Science Foundation.

SRI International is in the process of creating a new Center for Science Dynamics. The center aims to take a leadership role in the dialog on a science of science policy, metrics for science, access to data, as well as the challenges of research evaluation in a global context. This includes serving as the hub of a community of colleagues from around the world, holding workshops and seminars, and offering training and education. Lead is Caroline Wagner, S&T Policy Unit, SRI International <cswagner@gwu.edu>

A Consortium is being formed comprising major data and service providers with an interest to collaborate on a full suite of tools for science management. Lead is Barend Mons, Associate Professor in Biosemantics, Erasmus Medical Center and Leiden University Medical Center, the Netherlands. <bmons@knewco.com>

Over the last five years, my lab/center has been working on the design of cyberinfrastructures such as the Information Visualization CI (<http://iv.slis.indiana.edu>) and the recently funded Network Workbench CI (<http://nwb.slis.indiana.edu>) that can and have been used to conduct ‘computational scientometrics’ research. Recently, we have co-organized a number of workshops related to the data integration, analysis, modeling, and mapping of science:

- Dec 1 & 2, 2005: *1st Mapping Science Meeting* organized by Katy Börner and Deborah MacPherson at Thomson Scientific, Philadelphia, PA.
- April 4, 2006: *2nd Mapping Science Meeting* organized by Katy Börner and Deborah MacPherson at The New York Academy of Science, New York City, NY.
- May 21st, 2006: *Modeling Science Workshop* organized by Katy Börner and Robert Goldstone, Indiana University, Bloomington, IN.
- Aug 31-Sept 1, 2006: *Workshop on Scholarly Data and Data Integration* organized by Katy Börner, Stacy T. Kowalczyk, Barend Mons, Marc Weeber, Erik van Mulligen, and Miguel Andrade.

The meetings and workshops have helped pool and share resources. They have interconnected data integration, analysis, modeling, and mapping experts to potential ‘clients’ and funding.

To gain an overview of data/tool/computing and other resources available to the countries present at the *Workshop on Science of Science Policy* in Helsinki, I suggest to administer the questionnaire on page 11 and 12 of this paper. The results of the questionnaire analysis would give us a very first overview of the needs and resources that different countries possess.

Acknowledgements

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Biography

Katy Börner is an Associate Professor of Information Science in the School of Library and Information Science, Adjunct Associate Professor in the School of Informatics, Core Faculty of Cognitive Science, Research Affiliate of the Biocomplexity Institute, Fellow of the Center for Research on Learning and Technology, Member of the Advanced Visualization Laboratory. She directs the Information Visualization Laboratory and is the Founding Director of the Cyberinfrastructure for Network Science Center at Indiana University.

Her research focuses on the development of data analysis and visualization techniques that improve information access, understanding, and management. She is particularly interested in the study of the structure and evolution of scientific disciplines; the analysis and visualization of online activity, e.g., user actions in 3D virtual worlds; and the development of cyberinfrastructures (CI) for large-scale scientific collaboration and computation such as the Information Visualization CI (<http://iv.slis.indiana.edu>) and the recently funded Network Workbench CI (<http://nwb.slis.indiana.edu>).

She co-edited a book on 'Visual Interfaces to Digital Libraries' published by Springer in 2002, a special issue of PNAS on 'Mapping Knowledge Domains' published in April 2004, a special issue on 'Collaborative Information Visualization Environments' in PRESENCE: Teleoperators and Virtual Environments, MIT Press that appeared in Feb. 2005, and a special issue on 'Information Visualization Interfaces for Retrieval and Analysis' in the Journal of Digital Libraries that appeared in March 2005. She is also the co-editor of a special issue of Environment and Planning B on 'Mapping Humanity's Knowledge and Expertise in the Digital Domain'.

Börner is the recipient of many fellowships and awards, including Outstanding Junior Faculty Award, Pervasive Technology Laboratories Fellowship, SBC Fellow, NSF CAREER Award, and Trustees Teaching Award. She is currently PI or Co-PI on 12 grants that are funded by NSF, the James S. McDonnell Foundation, 21st Century Fund, and SUN Microsystems.

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Science of Science Policy Questionnaire
xxx, xxx, ... Katy Borner
06/27/2006

This survey aims to capture information on the data/tool/computing and other resources available to the different countries at the *Workshop on Science of Science Policy* in Helsinki. Your input is greatly appreciated.

Please list the databases that you access to make informed science policy decisions.

Please list the tools that you use to make informed science policy decisions.

What additional datasets would be useful for your work?

What tools/services would be helpful for you but are currently not available to you?

What do you see as the major challenges for a science of science policy?

What do you see as the major opportunities for a science of science policy?

What activities (meetings, funding) exist in your country that support a science of science policy?

Please list documents, white papers, etc. that provide further information on science of science policy efforts/results in your country.

Any other comments you might have are welcome as well.

Thank you for your time.