Modeling the Invisible College

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This paper addresses the invisible college concept with the intent of developing a consensus regarding its definition. Emphasis is placed on the term as it was defined and used in Derek de Solla Price's (1963; 1986) work and reviewed on the basis of its thematic progress in past research over the years. Special attention is given to Lievrouw's (1990) article concerning the *structure* versus *social process* problem to show that both conditions are essential to the invisible college and both may be reconciled. A new definition of the invisible college is also introduced, including a proposed research model. With this model, researchers are encouraged to study the invisible college by focusing on three critical components – the *subject specialty*, the scientists as *social actors*, and the *Information Use Environment (IUE)*.

Introduction

Research models are important to the field of Library and Information Science because they provide a set of themes to observe when collecting data for analysis and interpretation. Such models require testing with different populations, in different types of environments. With frequent testing the model should provide evidence over time that it has reached the status of a theory, or scientifically acceptable general principle or body of principles offered to explain a phenomenon.

One of the most noticeable gaps in the Information Science literature is that there has not been any development or use of a research model for the term invisible college. This finding is curious, particularly because it has appeared so frequently in various studies. A search for the phrase "invisible (W) college? /AB" (Abstract) in the Dialog™ *Information Science and Technology Abstracts* database and the database *of Library Literature and Information Science* yields, for instance, a list of 55 items. At least 55 scholars have used the term since 1964. A closer look at each individual study reveals, however, that the research is somewhat non-cohesive. Scholars are fascinated with the invisible college and its relationship to communication, knowledge growth, and collaboration in science, but they do not seem to agree precisely on what an invisible college is.

What is an invisible college?

The term invisible college was first used in seventeenth century Europe when the Royal Society of London was founded. Members of this early Royal Society of Scientists (many of whom were mathematicians) did not belong to a formal institution; but referred to themselves as an invisible college due to their geographic closeness and regular meetings based on shared scientific interests (Bartle, 1995; Lievrouw, 1990; Lingwood, 1969; Price 1963).

Later, Price's (1963; 1986) bibliometric research led to the modern identification of invisible colleges as groups of elite, mutually interacting and productive scientists from geographically distant affiliates who exchange information to monitor progress in their field. While his research focused on measuring *formal* channels of communication, specifically the growth of scientific literatures and collaborative work as evidenced by multi-authored papers, he used the term invisible college to emphasize *informal* patterns of interpersonal contact among scientists.

In order to examine "the tangible results of scientific work more deeply," Price (1963; 1986) emphasized the importance of learning "more about the social institutions of science and the psychology of the scientist" (1986, p. 56). The scientist's character, he said, is rooted in "the basic difference that exists between creative effort in the sciences and in the arts. The artist's creation is intensely personal, whereas that of the scientist needs recognition by his peers" (1986, p. 62).

Price's (1986) view of the invisible college was that it emerged from new groups of scientists; "groups composed of [a maximum] of 100 colleagues." These groups, he explained:

> devise mechanisms for day-to-day communication. There is an elaborate apparatus for sending out not merely reprints of publications but preprints and pre-preprints of work in progress and results about to be achieved.
>
> In addition to the mailing of preprints, ways and means are being found for physical juxtaposition of the members… For each group there exists a sort of commuting circuit of institutions, research centers, and summer schools giving them an opportunity to meet piecemeal, so that over an interval of a few years everybody who is anybody has worked with everybody else in the same category (pp. 74-76).

Past invisible college research

Previous research concerning the invisible college has suggested that it is a fairly organized system for scientists and that a certain degree of predictable behavior (i.e. information sharing and collaboration) can be found within this system (e.g., Crane, 1969; 1972; Griffith & Mullins, 1980).

Bibliometric or scientometric studies show that scientists involved in invisible college networks typically carry out research within a subject specialty. Most specialties are then made up of sub-topic areas with authors clustered together (i.e., cocited) centrally and peripherally according to shared research interests (e.g., Sandstrom, 1998; Zuccala, 2004). Information seeking within the invisible college is strongly associated with an individual author's cognitive identity and takes place mainly through socially mediated activities, such as graduate training or colleague recommendation (Sandstrom, 1998). Sometimes different, yet complementary subject areas form invisible college networks, and this occurs when there is a need for scholars to share human, financial or clinical resources (e.g., Lievrouw et. al, 1987).

Invisible college specialists communicate often with specialists from their main network, but they also develop "weak ties" to researchers outside this network (Granovetter, 1973; 1983). Ties with other scientists prevent researchers from becoming psychologically over-invested in one subject and allow them to focus on originality in problem solving (Crane, 1969; 1972; 1980; Cronin, 1982; Crawford, 1971). Matzat (2004) indicates that Internet discussion groups are

valuable now for providing access to social capital and allowing weak ties to develop, but that there is "no convincing evidence that they generate new collaborations in substantial numbers" (p. 246). E-mail use among scientific researchers has also become more prominent, but research shows that face-to-face communication is still mostly preferred among invisible college participants. E-mail is limited to scientists who know one another quite well: "it is used most by scholars who are collaborators or friends" (Koku, Nazer & Wellman, 2001, p. 1752). Collaboration networks among invisible college participants are also noticeably "thin" and have been found to exist within university departments as opposed to between them (Tuire & Erno, 2001).

Invisible colleges become more "visible" when scientists are grouped together within a defined boundary, regularly procure financial support, engage in a formal selection process and shared research vision, and participate in mandatory group meetings (e.g., White, Wellman & Nazer, 2004, p. 112). Scientists often make an effort to attending meetings because they appreciate the "the value of face-to-face [contact], formally presenting ideas...exchanging views with old and new colleagues, taking field trips, and having fun" (Brunn & O'Lear, 1999, p. 299). Most of these meetings are now advertised on the World Wide Web, and take place in well-developed countries (Brunn & O'Lear, 1999; Zuccala, 2004).

The growth of formal or published information in an invisible college is said to follow an "exponential distribution" on the logistic curve (Price, 1963; 1986). In cases where a linear distribution is observed, it is important to consider the impact of various external or sociological factors. Sometimes an invisible college cannot thrive because the subject area that informs interpersonal activity ceases to possess interesting or viable problems. Also, if the research environment is not supportive enough (both financially and psychologically) it may hinder scientists from training graduate students and traveling to other research centers to share ideas [e.g. Fisher's (1967) study of the Invariant Theorists]. Conversely, if the published information does follow an exponential distribution of growth, it may be the case that government funding is a significant factor. Government funding sets research agendas, which can foster research leading to the development of invisible colleges. Sometimes the resulting invisible college network is formed from hybrid problem areas (i.e., involving scientists from different backgrounds) as shown in Perry and Rice's (1998; 1999) research concerning developmental dyslexia.

In the midst of all previous invisible college insights, one of the main problems associated with the concept is that it is used to describe different phenomena and has already been assigned too many definitions. Clusters of interacting scientists with mutual research interests have been characterized as "the hierarchical elite resulting from an expectable inequality, and number about the square root of the total population of people in that area of research front" (Price, 1971, p. 75). Some researchers claim that invisible colleges are just simply "innovation cliques" (Van Rossum, 1973) or "social circles" made up of smaller, fragmented "schools" (Crane, 1972; 1980; Kadushin, 1966). Others believe that an invisible college is a tightly meshed community - "it selects its own society, then shuts the door" (Paisley, 1968, p. 6). Another view, expressed by Cronin (1982) is that the invisible college is disadvantaged as an informal communication system since it is at risk of being unstable, short-lived, expensive to maintain and resistant to institutionalization. In a similar vein, Mulkay, Gilbert and Woolgar (1975) assert that invisible colleges are "concentrations of research ties without clear boundaries … amorphous social groupings … in a state of constant flux, partly due to overlapping personnel and to migration" (p. 190).

Further to all definitions of what an invisible college "is," Paisley's (1969) theoretical review helps to confirm what an invisible college is not, or more importantly, where it fits within a larger system of scientific communication. Paisley (1969) acknowledges Price's (1963) contribution, and inserts the invisible college within a system that includes the scientists' *work team, professional membership group, reference group,* and *formal organization*. For instance, the *formal organization* (real university or college) emphasizes "roles, lines of responsibility and products rather than people themselves" (p. 6). The scientists' *professional membership group* ("I am a mathematician") controls "the 'official' information channels of the scientist's field" (e.g., primary journals and monograph series), whereas the invisible college does not (Paisley, 1969, p. 5). An invisible college is similar to a *reference group*, "which includes other scientists with similar specialization, similar training, excellence of work, or other characteristics," but it is better described in terms of a subsystem, comprised of a smaller number of international researchers and designed for "direct access" (p. 5). Also, even though the scientist may save papers and reprints from researchers belonging to his/her reference group, (s)he "is more likely to arrange meetings, plan joint projects and co-author works with participants of the same invisible college network" (p. 5).

Despite the list of varied definitions, there is some reassurance that the invisible college "is likely to remain a pivotal feature of the scientific communication system for the foreseeable future" (Cronin, 1982. p. 232). According to Cronin "advances in communications technology, coupled with the likely growth in interdisciplinary research suggest that the management and promotion of invisible colleges throughout science could prove to be an area warranting careful thought and investigation" (p. 232).

The invisible college problem

Price originally coined the term "invisible college" in reference to an *informal* communication network of scholars; however, Lievrouw (1990) argues that this idea of informality has not been reflected well enough in the research literature. There is a lack of real information about invisible colleges because researchers tend to focus more on products of scholarship (i.e., documents and citation data) and/or network structures rather than on the actual communication processes of people who do scholarly work. For instance, Crane (1972) examined the growth of two specialty literatures, one in mathematics and one in sociology, and approached the issue of informal communication by collecting survey data on co-authorship patterns and the exchange of preprints. Her survey questions focused on gathering information about formal communication activities – activities that facilitate the production of documents, and Lievrouw (1990) believes that the data should not have been construed as examples of *informal* behaviour (p. 63, original emphasis).

Lievrouw's (1990) assessment of Crane's (1972) study and other similar studies is that the term invisible college is frequently misused or given different meanings for different purposes. In light of this, she raises an important question: are invisible colleges *structures* of scholarship (discernable and measurable from outside elements – i.e., published documents) or are they *social processes* rooted in informal human behaviours, perceivable only to those who carry them out? (p. 66). To reconcile the structure versus process problem, Lievrouw (1990) recommends the following:

> If the invisible college is to be an informal social phenomenon then a revised definition can be proposed: *An invisible college is a set of informal communication relations among scholars or researchers who share a specific common interest or goal* (p. 66; original emphasis).

With this definition, there is no assumption that an invisible college is rooted in a prerequisite formal institutional structure (p. 66).

Lievrouw's (1990) second recommendation is that future research concerned with the invisible college should be based on a new set of issues. For example: How do individuals perceive their interactions with others within, versus outside of, the invisible college? How do individual scholars use invisible colleges as resources to help fulfill their information needs? (p. 67).

Her third recommendation is that ethnographic methods of research, in addition to bibliometrics should be used in studies of scholarly communication. Lievrouw (1990) concedes that bibliometric analysis is an effective technique for producing "maps" of documents and that such maps offer a "systematic glimpse of the communication acts that produced the documents in the first place" (p. 68). On the other hand, if the goal is to understand underlying "informal" aspects of communication (i.e., mentoring, collegiality, or collaboration) she insists that qualitative techniques of research, primarily participant observation and interviewing, have the potential to give the researcher more "interpretive and heuristic" power over a study (p. 68).

For the most part, Lievrouw's (1990) research observations and recommendations are valuable. She identifies a major problem concerning the invisible college – the *structure* versus *social process* problem – and advises future researchers to organize new studies that will help lead us towards a solution. Nevertheless, her proposed definition requires further consideration. This definition sets the invisible college apart from communication systems rooted in formal structures, thus my argument is that it may be too narrow.

Derek de Solla Price (1963; 1986) referred to the invisible college as an informal communication network of scholars – elite scholars from different research affiliates who belong to an "in-group" of approximately 100 people. According to Price, the "people in such a group claim to be reasonably in touch with everyone else" and have the power to confer power and prestige on one another. With respect to how the group members stay in touch, he specified that they "meet in select conferences (usually held in rather pleasant places), they commute between one center and another, they circulate preprints and reprints to each other, and they collaborate in research" (1986, p. 119). Moreover, he stated that the members contribute "*materially*" to research in a subject area and that they not only do so "on a national scale," but also on an international scale, including "all other countries in which that specialty is strong" (1986, p. 119, emphasis added).

Price's (1963; 1986) recognition of the *material* contributions of invisible college members is significant because it implies that published documents are relevant to the invisible college phenomenon, even if the production of these documents is not the sole purpose for its existence. When the participants of an invisible college network do generate work for publication, and when an attempt is made to trace the links between their publications, there is an opportunity to gain insight into their shared research interests – interests that comprise their subject specialty. As a result, the subject specialty, rooted in documented evidence, may be viewed as the structural component of the invisible college, whereas the invisible college itself is the

underlying social component. Hagstrom's (1970) understanding of the relationship between the two terms, invisible college and subject specialty, provides further clarification:

> the set of scientists in a discipline who engage in research along similar lines can be called the scientific specialty. It is reasonable to believe that scientists will communicate most often and intensively with others in their specialties, exchanging preprints with them [and] citing their work… There is some evidence that "specialties" are not "invisible colleges" – or tightly knit networks of communication .. [yet] most specialties in science are quite small enough so that they could be tightly knit communication networks even if they are not so in fact (p. 91-92)

Given both Price's (1963; 1986) and Hagstrom's (1970) explanations, it is clear then that an invisible college can exist within a *subject specialty,* but a subject specialty is not necessarily an invisible college.[1] In effect, the *structure* versus *social process* problem also becomes more obvious. There may be a lack of real information about invisible colleges, as Lievrouw (1990) suggests, because it is easier for researchers to study the specialty or structural component rather than the interpersonal or social component. Most documents associated with a subject specialty are readily available to researchers through bibliographic indexes and can easily be submitted to bibliometric analyses. But, even though it easy to access documents and create bibliometric maps of the intellectual structure of scholarship, it can be problematic to assume that they reveal much about underlying informal communication.

Conversely, if Lievrouw's (1990) proposed definition of the invisible college is adopted, with its emphasis on the "set of informal communication relations among scholars or researchers, who share a specific common interest or goal," another set of problems may arise. For instance, it can be difficult to determine who is participating in an invisible college network, if the shared goal that has cultivated interpersonal relationships within that network is not identified. In other words, it is not efficient to examine how individual scholars make use of personal contacts to satisfy information needs if there is no prior understanding of the intellectual basis for their needs in the first place - their *subject specialty*.

To understand the true nature of the invisible college, it is important first to recognize then that it is not a one-dimensional construct, but rather a multi-faceted phenomenon. Second, we need to establish a clear definition that remains open to all of its multi-faceted components. My definition is the following:

> An invisible college is a set of interacting scholars or scientists who share similar research interests concerning a subject specialty, who often produce publications relevant to this subject and who communicate both formally and informally with one another to work towards important goals in the subject, even though they may belong to geographically distant research affiliates.

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[1] How the specialty itself has emerged can vary. It may have branched from a broader discipline or it may be the result of an intersection of two or more disciplines, forming a specialty area now functioning as an invisible college network [see Perry & Rice's (1999), developmental dyslexia study]. An example of a specialty that does not form an invisible college network might be cryptography research groups in different world regions who are interested in the same problems but secretive about their work for security reasons.

With this new definition, researchers have an opportunity to focus on the different types of contributions that bibliometric, sociometric and ethnographic (or qualitative) modes of analysis can make to the study of invisible colleges. Bibliometric analyses typically focus on cognitive forms of interaction (e.g., scholars citing each other), while sociometric analyses can help to clarify social forms of interaction (e.g., scholars meeting with each other at worldwide conferences). Qualitative forms of analyses are again unique in their focus on detailed ways of behaving and communicating (e.g., competitive behaviour; collaborative behaviour). Overall, the above definition opens up an opportunity to graphically superimpose sociometric on bibliometric data as a means for creating "representations of a specialty based on citation and its variants, co-authorship, colleagueship, trusted assessorship, mentorship" - factors that "would corroborate the [invisible college's] spatial and temporal dimensions" (Chubin, 1976, p. 455). Other invisible college researchers, for example, Crane (1972), Lievrouw et al. (1987), Sandstrom (1998) and Perry and Rice (1998) have combined or integrated sociometric, bibliometric and qualitative data to obtain insight; however, in light of Chubin's (1976) suggestion there are different ways of working with data, including the methods presented in this paper.

5. Modeling the invisible college

Consider now the value of modeling the invisible college – i.e., creating a research framework – to correspond with the above definition and method. The model should be a visual representation of its primary components, so that each component interacts with the other, and can be considered sufficiently within the context of a study.

The invisible college model that I wish to highlight is one that is derived from the previous work of Rosenbaum (1993, 1996). Rosenbaum was the first to develop a structurationally informed value-added model for the study of organizations. Originally his "structurational" approach was used to examine information behaviour in a management organization; however, its significance is that it can be generalized to various types of organizations, including scientific organizations like invisible colleges.

Rosenbaum's model, illustrated in Figure 1, stems from a merging of Taylor's (1991) value-added perspective of Information Use Environments (IUEs) with Gidden's (1984) theory of structuration. When combined, the two theoretical perspectives are said to create "duality of structure." Duality of structure is a more effective way of understanding "how the information behaviours [of social actors] and social environments mutually and simultaneously constitute each other" (Rosenbaum, 1993, p. 235). Specifically this means that individuals who interact with one another in social situations can be influenced by the structure of their IUE. At the same time, the IUE can also "be a product or consequence of [how individuals engage in] social action and interaction" over time (p. 79).

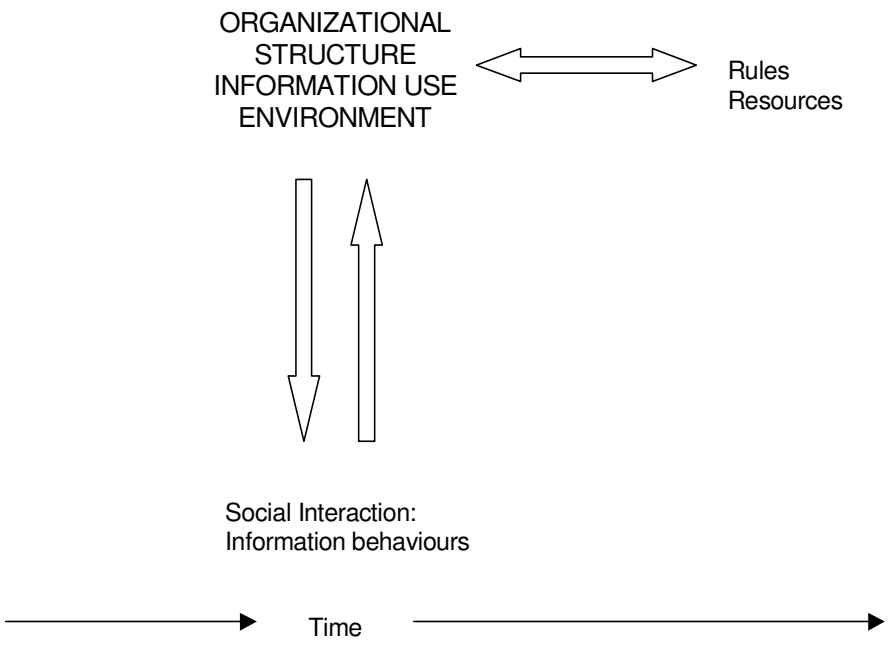

Figure 1. Rosenbaum's original model of a structurationally informed value-added approach to organizations (Adapted from Rosenbaum, 1996, p. 101).

For a new study concerning a scientific organization, or invisible college, there is no need to alter the structurational and temporal aspects of Rosenbaum's (1996) model, or disregard the dual nature of social interaction and the **IUE**. These elements are important and shall be retained; however it is necessary to introduce a few modifications. First a new label is added, termed the **social actors.** Second, the rules attributed to the **IUE** are shifted to another component termed the **subject specialty**. The resulting new model, shown in Figure 2, now presents a series of interconnected ovals designed to highlight the interrelationship between 1) the **subject specialty**, 2) the **social actors**, and d) the **IUE**.

The space that intersects the **IUE**, the **subject specialty** and the **social actors** produces an organizational structure termed the **(in)visible college**. An **(in)visible college** may or may not be visible, depending on its association with a particular type of **IUE**. Some **IUE'**s are grounded by a physical space, while others or not; thus the **IUE** is basically "the set of elements that affect the flow and use of information messages into, within, and out of any definable entity" (Taylor, 1986, p. 3). If the **IUE** is established as a physical space, it has the potential to fortify an **(in)visible college** with the provision of human, physical and/or technological resources.

The **subject specialty** is important because it informs the **(in)visible college** of its disciplinary rules and research problems. The rules or problems may be transferred from background discipline(s) or newly developed and agreed upon by the scientists who believe that they are more suitable to the specialty area's research focus.

The scientific researchers who understand and agree upon the rules and interact one another to solve research problems are the **social actors**. **Social actors** make use of the **(in)visible college** to support their information seeking and sharing patterns, but they may also reinforce or "instantiate in action" the **(in)visible college** through the contribution of bibliographic artifacts, or evidence of scientific achievement for preservation (Rosenbaum, 1996, p. 112).

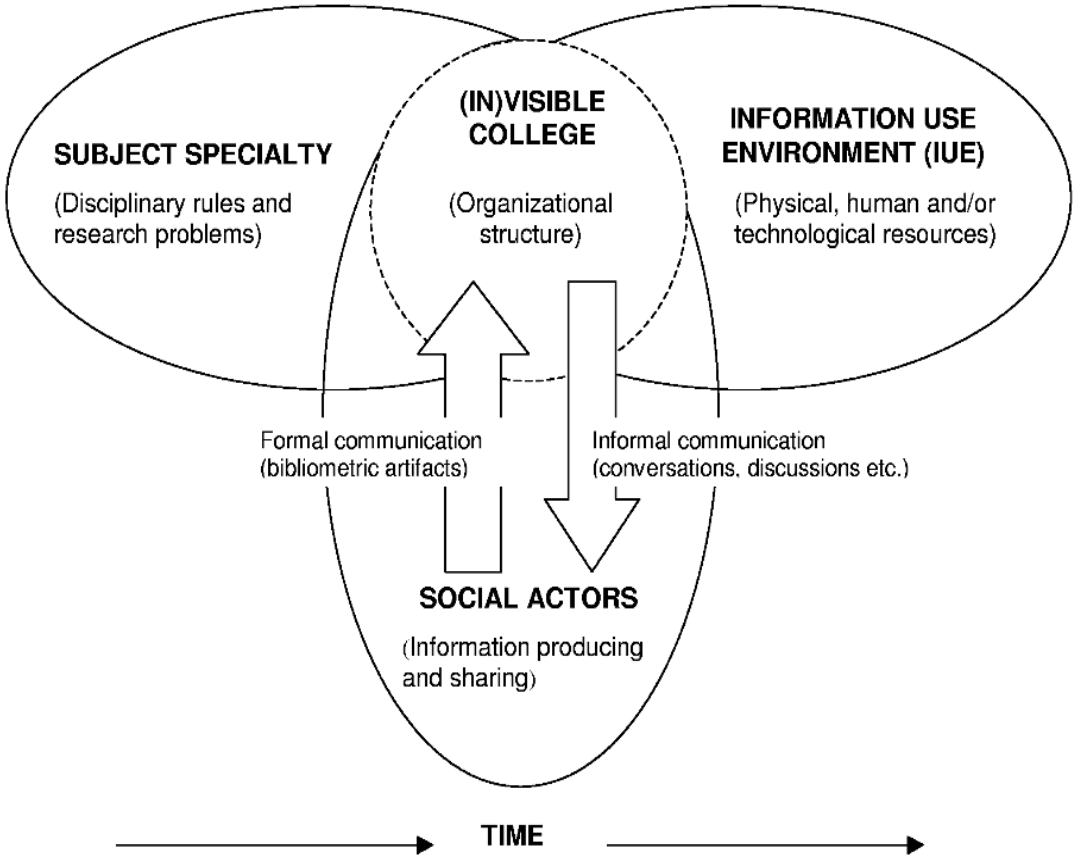

Figure 2. Structurationally informed value-added model for the study of scientific organizations.

Research Implications

The subject specialty

The first component of the research model termed the **subject specialty** provides a starting place for an invisible college study. Again, the subject specialty is significant because it informs the invisible college of its disciplinary rules and research problems. It also supports the intellectual motivation for social activity, where scholars are expected to interact with one another for information sharing or collaborative research. Clearly, a subject specialty is not necessarily an invisible college, or close-knit communication network, but there are some specialty areas of research in the sciences and social sciences that will provide "hints" as to why they may function as such. The following questions should help the researcher as he/she looks for these "hints":

1) *How young is the subject specialty?* (It cannot be too old in the sense that many of the foundational scholars are either deceased or not publishing in the area anymore).

2) *Does the subject specialty fit within an identifiable indexing or classification system?* (e.g., the American Mathematical Society Classification Code).

3) *Is there a World Wide Web page associated with this specialty where participants have access to current research information (e.g., preprints), including information regarding national/international conference activities?*

4) *How many scholars are identified with this specialty area*? (If there are too many scholars, the subject specialty is likely too large for members to know one another and interact with each other informally).

5) Are the scientists/scholars distributed worldwide? (There is no rule that suggests invisible college members must be international; however, if they are and there is evidence that they meet at selected conferences, there is an added richness to the kind of interpersonal communication that takes place).

Once a subject specialty is identified, it can then be structured for visual examination using the Author Cocitation Analysis (ACA) technique, developed by White and Griffith (1982). Traditionally, this technique makes use of the individual author's oeuvre (single or co-authored document(s) of which (s)he is the first author) and assumes that two authors are intellectually related to one another if they are co-cited frequently together in many documents (White, 1990). A complete ACA involves the selection of author names, the retrieval of (first) author cocitation frequencies, the compilation of a raw data matrix and conversion to a correlation matrix, and the multivariate analysis of the correlation matrix for interpretation and validation (see McCain, 1990). The end result is a bibliometric map or visual "picture" of the specialty, comprised of clustered author nodes.

ACA has been used to investigate a variety of specialty areas in the sciences and social sciences (e.g., Bayer, Smart & McLaughlin, 1990; Ding, Chowdhury & Foo, 1999; Karki, 1996; Perry & Rice, 1998; White & McCain, 1998). It is not a new research technique and has been the topic of important methodological discussions in past years (e.g., Ahlgren, Jarneving &

Rousseau, 2003; Persson, 2001; Rousseau & Zuccala, 2004; White, 2003). Within the context of invisible college research ACA is particularly valuable because it produces a bibliometric "map" and a map can be a valuable navigation tool.

The initial benefit of producing a bibliometric map of a subject specialty is that it provides a historical "snapshot" of how the research area has evolved up to a particular point in time. Within the specified time frame, for instance 50 or so years (1950-2000) the piling up of cocitations may be significant enough to determine author relationships. Traditionally, the interpretive approach in ACA focuses on discovering what the author clusters and map dimensions "represent in terms of scholarly contributions, institutional or geographic ties, intellectual associations, and the like" (McCain, 1990, p. 441). White (1990) suggests however that the ACA map might have another purpose beyond the traditional approach. Certainly co-cited author relationships can be observed in terms of intellectual influence, but "many relationships other than intellectual influence are reflected by citations, and some influences are not captured by citations at all" (p. 94).

With a bibliometric map in hand, the scholar who studies an invisible college has a specific advantage in that he/she can focus on investigating underlying facts concerning past and present relationships among scholars within the subject. The map can act as a travelling aid in that scholarly territory, where "fieldwork techniques [i.e., interviews; participant observation] typical of ethnographic studies of communication" may be used to gain more "interpretive power" (Lievrouw, 1990, p. 68). A semi-structured interview, for example, may be designed so that the ACA map is taken out into the research field and used as a discussion piece during the interview process. Authors selected for an ACA can be invited to participate in the interview either face-to-face (e.g., at a conference) or by e-mail. As authors are shown a copy of the ACA map, they have the opportunity to see which authors belong to their intellectual cluster and comment on personal relationships. Related stories can then be used to explain underlying elements contributing to the map's structure that would normally be left to assumption. A bibliometrician cannot assume that if author A and author B are co-cited that they are socially connected. However, if author A shares information about his/her personal relationship with author B (and vice-versa) then the social dimension of the cocitation may become more evident: the two authors may be friends, faculty colleagues and/or have had a significant mentoring connection as research advisor and student.

Figure 3 provides an example of a cocitation network created for a group of authors (n=75) involved in a specialty area of mathematics known as Singularity Theory.[2] Singularity Theory has experienced a significant period of development in the past 60 years. Trotman (1999) details the history of this specialty *in Le Dictionnaire d'Histoire et Philosophie des Sciences*, noting that mathematicians first began to study curves with singularities at the School of Alexandria in ancient Greece. Singularity Theory as it is known today, however, is largely based on the major contributions of Milnor, Arnold, Hironaka, Thom and Lojasiewicz during the 1960s and 1970s. The classification of Singularities was only just completed as recently as 1979 (Isaac Newton Institute Annual Report, 2001, p. 24). Also, Singularities research has emerged recently as a distinct class code within the 1991 and 2000 American Mathematical Society Classification system. For example: Singularities (32Sxx; 1991- now) and the Theory of

[2] A singularity is defined as "the strange but remarkable point among anonymous non-singular points" (Trotman, 1999, p. 866).

singularities and catastrophe theory (58Kxx, 2000-now). Due to its presence within the AMS Classification system we know that it is a mature specialty, but it is obviously young in comparison to the main cognitive underpinnings of mathematics (e.g., 14-XX – 1940-now – Algebraic Geometry).

With respect to the invisible college phenomenon, Singularity Theory serves as an appropriate subject for analysis because the broader areas in mathematics include too many mathematicians and possess ancient roots that make them impossible to examine from a sociocogntive perspective. As a relatively small, but mature subject then, Singularity Theory possesses certain characteristics that suggest that it has been functioning as an invisible college. For instance, a European Singularities network site is now posted on the Web and at this site the names of mathematicians worldwide (approximately 100) working in this specialty area are listed. Links to preprints are posted and available for downloading, and there is also a list of past and future Singularity Theory conferences or workshops, which are important events for the mathematicians to meet personally and share new research information (European Singularities Network, 2000).

In Figure 3, the ACA of Singularity Theory has produced a cohesive "puzzle-like" structure, with an overall connectivity ratio of 63%.[3] Note that three sub-topic clusters have been identified and labeled as a result of a CLUSTER routine carried out in SPSS, with boundaries drawn as dashed lines. All authors belonging to the individual clusters are considered to be intellectually similar to one another; however the dashed lines indicate that there is a degree of boundary permeability: some of the authors have worked within more than one Singularity Theory topic. The following questions indicate the type of open-ended interview strategy a researcher might use to gain insight into some of the underlying social (invisible college) dimensions associated with the authors' nodal proximity. *Does the structure of this map make sense to you? Can you explain why? Do you recognize any of the author names next to your name on this ACA map? Tell me about some of the personal connections, intellectual or otherwise, that you currently have or have had with some of the mapped authors.*

Depending on the extent to which the researcher uses the interview process, (s)he could obtain information to form yet another view of the ACA authors, emphasizing a pattern of mentoring relationships or alternatively, the national 'schools' in which the scientists have worked together. Figure 4 captures a view of the national 'schools' associated with Singularity Theory.

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[3] Details associated with the data collection and ACA mapping procedure for the Singularity Theory map may be found in Zuccala (2004).

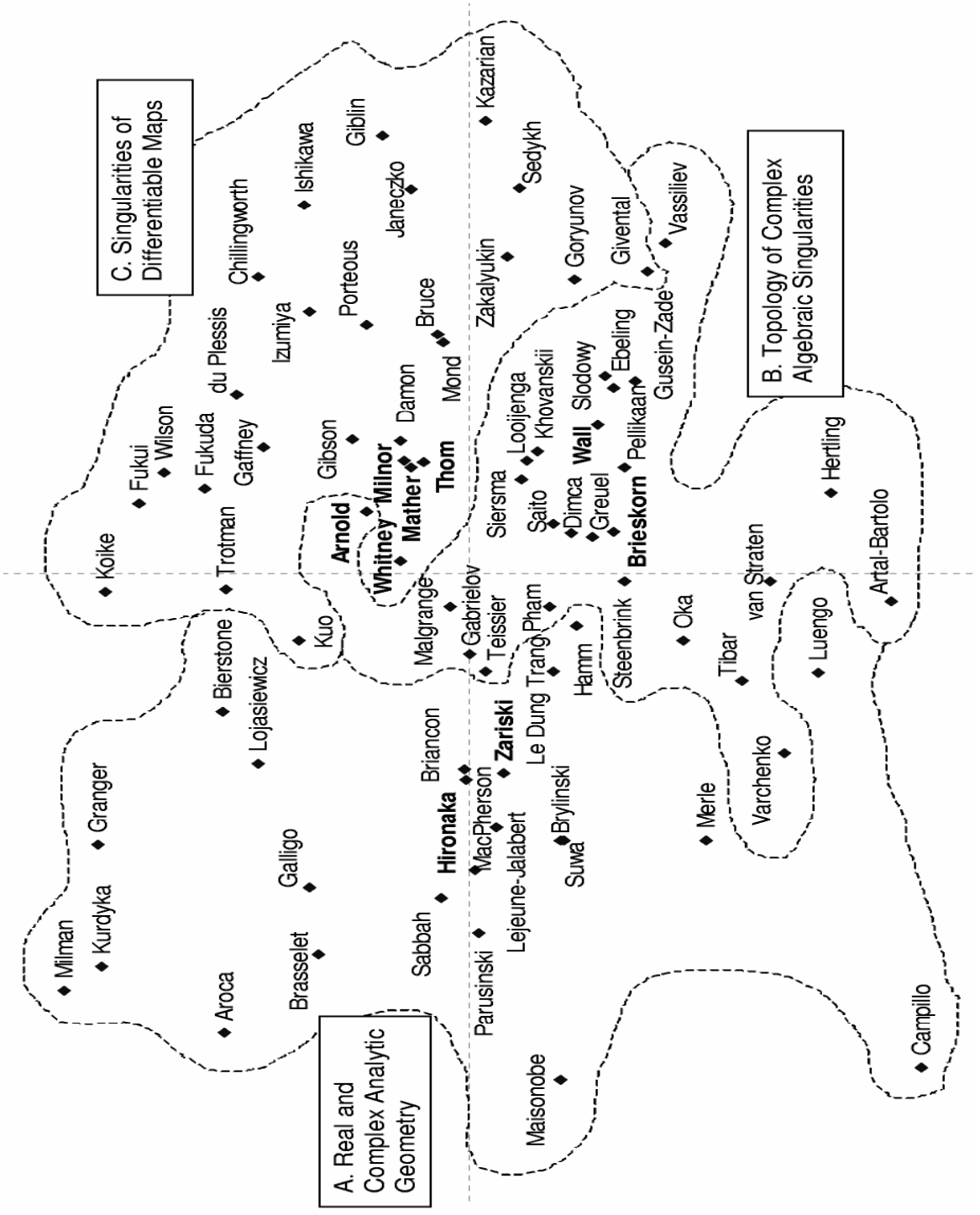

Figure 3. Author Cocitation map of Singularity Theory (1974-2000).

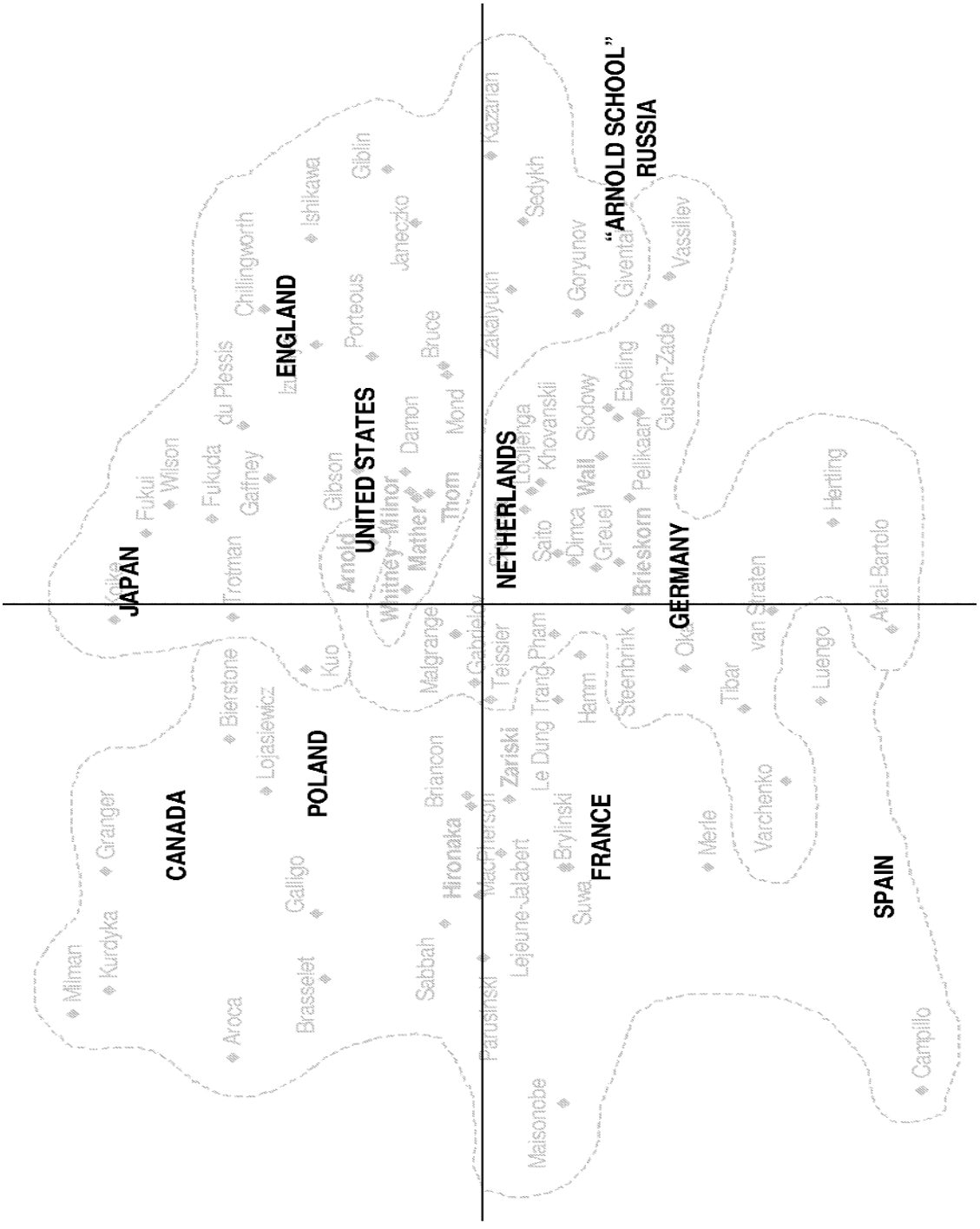

Figure 4. National research groups or "schools" in Singularity Theory (1974-2000).

In Figure 4, the "Arnold School" of Russia is uniquely labeled because the Singularity Theorists recognize this school in connection with its influential leader – Professor Vladimir Arnold. Zuccala (2004) spent time interviewing the students of Arnold to learn more about the nature of this 'school' and explains (using interview data) how a national 'school' might also be identified in cultural terms, for example, the French "style" of doing mathematics (p. 109).

Scientists as social actors

While an ACA structure of a subject specialty presents a fairly accurate picture of the intellectual connections between authors, it still does not satisfy the idea that an invisible college is a multi-faceted phenomenon. To ascertain why a subject specialty has become an invisible college, or close-knit communication network, a second research strategy is needed to determine which of the authors identified within the ACA have been involved with one another as **social actors**. Social interaction among scientists can occur through a variety of activities; however, with the new invisible college definition the most pertinent is the authors' collaborative habits and collegial interactions as conference participants.

Collaborative work is a form of social behavior, which draws upon the personal knowledge of the individual, but provides the individual with a unique learning experience situated in a co-operative context. A collaborative exchange between two or more researchers influences the perception of an information need by minimizing the private intellect in favor of focusing on the social aspect of the need. It can be as informal as a casual research discussion intended to enhance the work of one researcher, or as formal as two or more authors working together towards the completion of a joint publication.

Because collaborative work is variable in nature, research on the subject has been extensive, ranging from studies of co-authorship to qualitative investigations into scientists' everyday work activities (e.g., Beaver & Rosen, 1978; 1979a,b; Kraut, Galegher & Egido, 1988; Laudel, 2001). In many collaborative situations, Kretschmer (1997) explains that "birds of a feather flock together: [scientists] are guided more or less by a deliberate search for persons and this search is mainly controlled by the similarity of characteristics" (p. 581). With this in mind, several authors involved in an invisible college network are likely to have collaborated with each other frequently both formally and informally. Their "similarity characteristic" is based on the idea that they have all shared a commitment to the development of their specialty and/or or solution to the subject area's problems.

Collegiality or collegial interaction constitutes another form of social behavior, but unlike the notion of collaboration, it has not been examined as frequently. Different types of behaviours constitute collegiality, but in a narrow sense, it can refer to a relationship or social "tie" that exists, with some measure of strength, or does not exist between two scientists, depending on their act of participating in the same conference.[4] Scientists as social actors are collegially involved with one another for the purpose of keeping in touch and remaining up to date with what others are working on within the specialty area. No assumptions can be made

[4] In addition to conference-based collegiality, the term collegiality possesses another important relationship to scholarly acknowledgements. Cronin's (1995) book entitled *The Scholar's Courtesy* focuses on the practice of acknowledging colleagues whose comments or actions make it possible for others to conduct quality research. Colleagues often inspire one another and it is through informal inspiration that researchers often recognize a sense of intellectual debt.

about specific actions at a conference, for example, that author A actually met and had a research discussion with author B, although it is certainly possible. Again, Price (1986) first recognized the role of collegiality when he explained: "people [within invisible colleges] claim to be reasonably in touch with everyone else." They "meet in select conferences (usually held in rather pleasant places) and commute between one center and another" (p. 119).

To measure both collaborative and collegial activity within a subject specialty, data based the scientists' co-authorship patterns as well as their conference attendance patterns can be collected and analyzed in a joint ACA-Social Network Analysis. At this stage of an invisible college study, the original ACA map of the specialty plays an important role, because it acts as the original structure upon which to superimpose the distinct co-authorship and collegiality networks.

Co-authorship data for a joint ACA-Coauthorship map can be retrieved from any science or social science database that specifies the author (AU) as an indexed field. For example, using the Dialog™ *MathSci* database one must type the following search string: "AU=Author A AND AU= Author B" to retrieve all publications listing both Authors A and B as co-authors. The final count associated with each individual publication is then added to an adjacency matrix where Author A and Author B are joined together by one cell. If Author A and Author B have never published a paper together, no co-authorship count is possible; thus a 0 is added to their common cell.

To collect data for an ACA-collegiality map, a more exhaustive search is required. It is not possible to rely on an indexed conference participant database; therefore collegiality data must be traced through proceedings posted on the Web. The Web site of a particular conference generally includes a link to a final participant list from which the researcher can manually collect data. Author A and Author B, for instance, can be given 1 collegialty count, plus any incremental counts of 2, 3, 4 etc if they have attended many of the same conferences. A value of 0 is added to the cell adjoining the two authors if a discovery is made that the pair has in fact never attended the same conference. In cases where a conference participant list cannot be found on the Web, and data from retrospective years is needed (e.g., 1980 or earlier), published monograph proceedings can be a reliable source for information. Moreover, if all other resources are not applicable or attainable, the researcher can sometimes acquire collegial data by communicating directly with a conference organizer who has maintained accurate conference participation records.

Once the co-authorship and collegiality matrices have been developed, social network analysis tools, like UCINET (Borgatti, Everett and Freeman, 1999) and Krackplot (Krackhardt, Blyth & McGrath, 1995) can be used to construct maps or sociograms similar to the Singularity Theory maps shown in Figures 5 and 6. Specifically, each matrix is transformed into a unique .kp file by UCINET and used as input to the Krackplot network visualization software. Krackplot will retain the original proximity of the author nodes generated by the ACA, and support the superimposition of the social network ties to illustrate which authors in the ACA structure are connected. In Figure 5 we see that the co-authorship activity among the Singularity Theorists is somewhat thin, although a select number of authors actually have very strong ties to one another. Collegial interaction, shown in Figure 6, is by comparison more pronounced. A lot may be said about the two different types of social interaction, particularly in the field of mathematics. In this paper, full interpretations are not provided; however it is clear that the data are useful for analyzing what the different patterns mean. Interpretations can be made at a visual level, just by looking at the maps, but they can also be carried out at a statistical level based on a

QAP correlation analysis of the three matrix-based networks using UCINET [Borgatti, Everett and Freeman, (1999); see Zuccala, (2004)]. *What is the co-authorship structure of [subject specialty] and how does this structure relate to the specialty's intellectual (ACA) structure? What is the structure of collegiality in [subject specialty] and how does this structure relate to the subjects intellectual [ACA] structure and co-authorship structure?*

If the researcher needs to look at the invisible college's underlying social program (s)he may take the maps one step further into a qualitative stage of analysis. The maps can be used during a period of fieldwork, where inquires can be made about the social conditions that supported the co-authorship and collegial pairings in the first place. *What led you to collaborate so frequently with author X ? How did your collaborative efforts result in a co-authored paper? What are some of the factors that inspire you or have inspired you to collaborate formally with other authors? What has motivated you to participate in [subject area] conferences in past years? Why did you participate in some conferences and not others? What are some of the things that you value most when participating in a [subject area] conference?*

One of the benefits of doing fieldwork in conjunction with bibliometric and sociometric research techniques is that insights may arise that will not necessarily emerge through the use of one research technique alone. A strict use of ACA for instance might suggest that the authors appearing on the ACA map are the *only* individuals who participate in the invisible college activities. Fieldwork allows the researcher to witness more current patterns or behaviours. For instance, Zuccala (2004) interviewed authors who were not included on the Singularity Theory ACA-social network maps, but who were becoming involved with the invisible college as graduate students, research "newcomers" or distinctive invitees to the specialty area's conferences for the purpose of fostering cross-disciplinary fertilization. She also interviewed one author who has been cognitively active within Singularity Theory research for many years (i.e., noted on the ACA map), but claims to have left the specialty, even though he likes to participate in the conferences from time to time (pp. 179-189).

The scientists' information use environment

In order to do research, scientists, as social actors are dependent on space. A research "space" can be a laboratory or an office, or it can be an internet-based environment designed to facilitate observations and experiments, the flow of ideas and facts, and the need for discussion. Whenever or wherever a certain amount of space has been constructed for science, information and its artifacts (e.g., data; publications) are likely to be found within. In which case, a scientific workspace can also be referred to as an information environment or more precisely, an **Information Use Environment (IUE).**

Certain IUEs are critical to research concerning an invisible college not only because they supports invisible college activity, but because they may also make this activity more visible. If an IUE is grounded by a physical space (e.g., a specialized building or institute), socially mediated behaviours, which occur within the invisible college, can be more easily observed. The IUE essentially becomes an important space for the researcher who is inspired to engage in qualitative fieldwork.

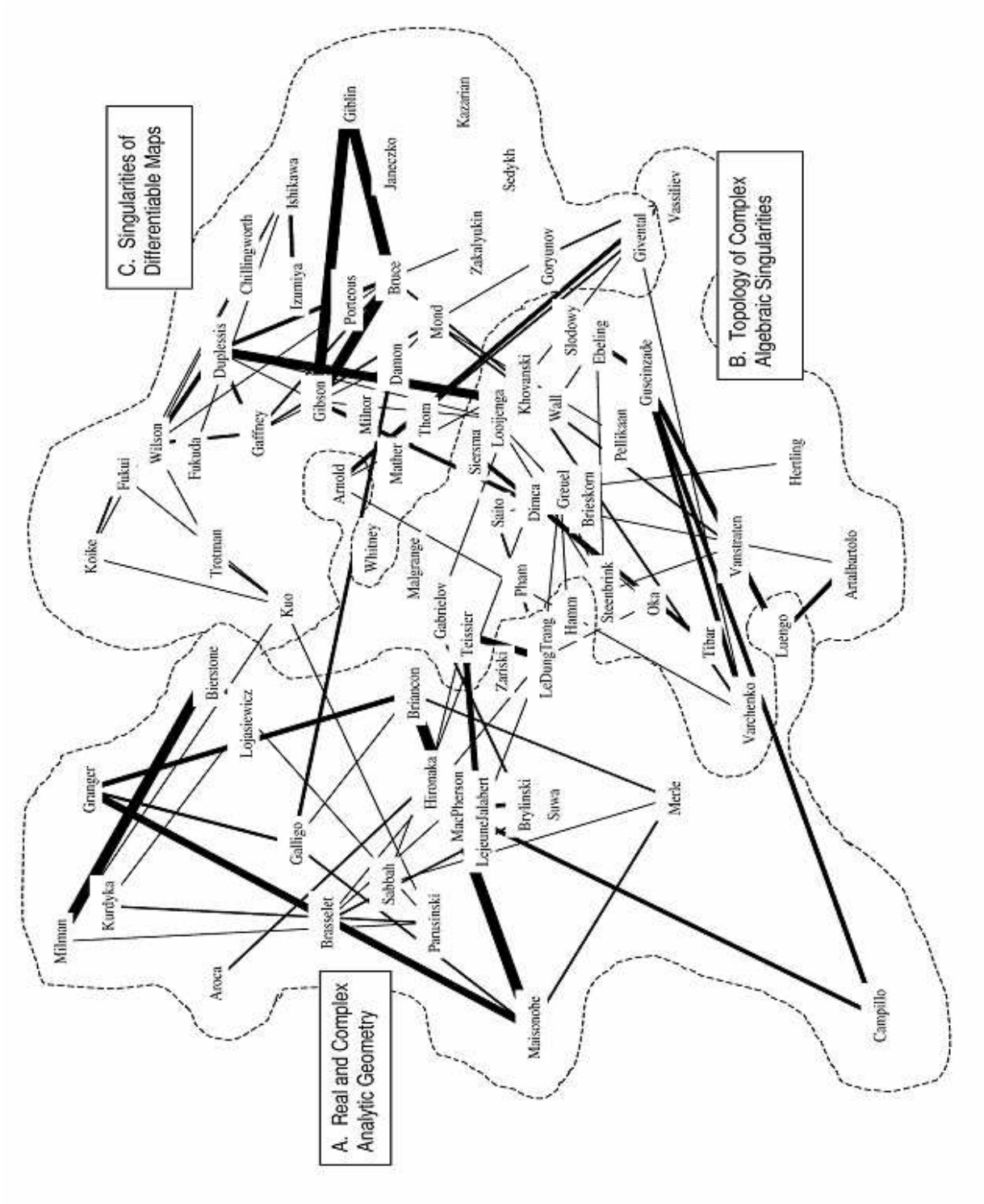

Figure 5. ACA-Co-author map of Singularity Theory research (1974-2000).

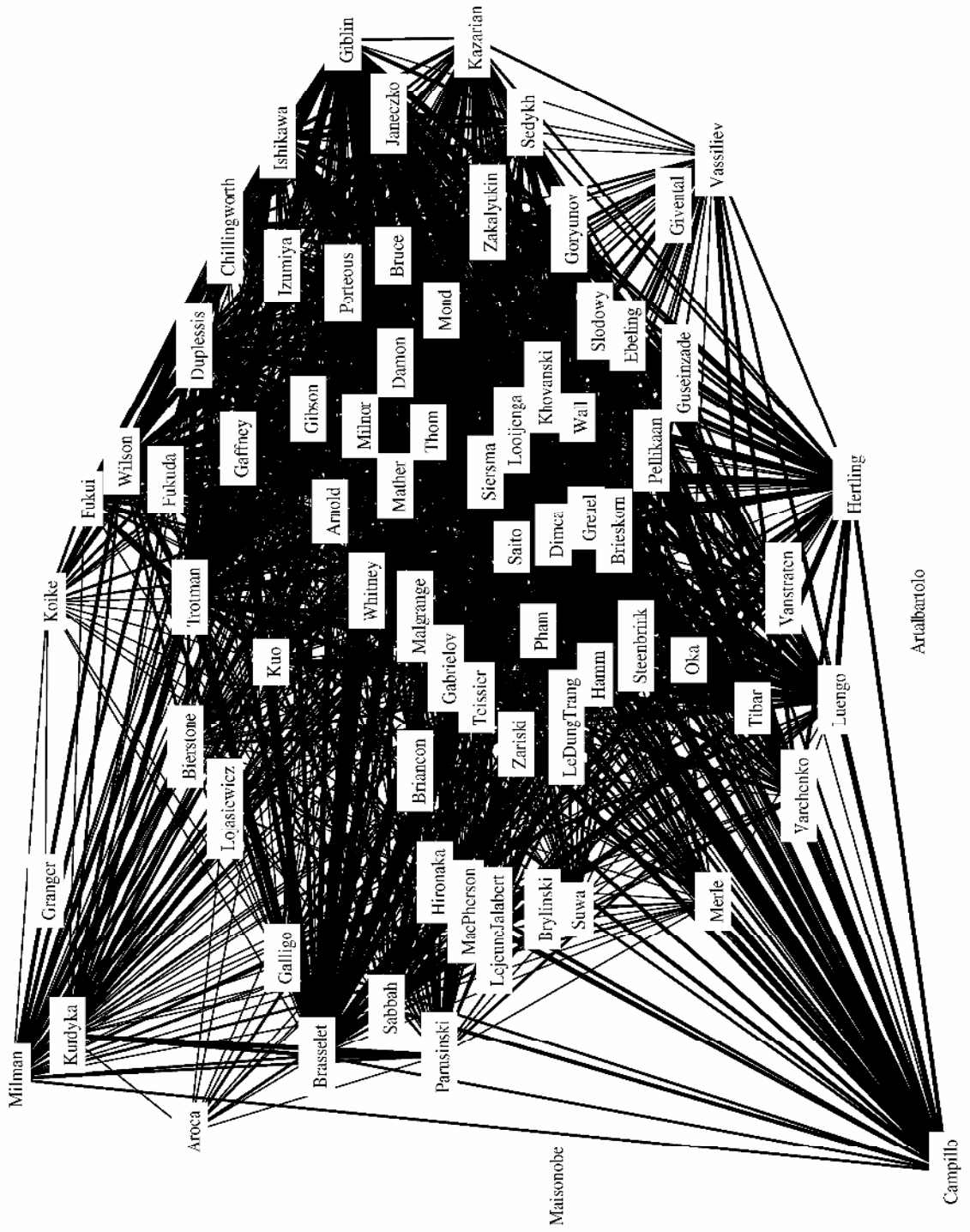

Figure 6. ACA-Collegial map of Singularity Theory research (1970-2000).

In past years, very few studies concerning Information Use Environments have been carried out in the field of information science (e.g., Kinsella). More often than not, research concerning scientists' IUEs has occurred in sociology. Among sociologists of science, physics and biology laboratories have been the main choices for ethnographic fieldwork and the social constructivist view science, a predominant research theme (e.g., Knorr-Cetina, 1981; 1983; Latour & Woolgar, 1979; Merz, 1998; Traweek, 1988). Social constructivists believe that science is mainly a contextualized activity, or more precisely that "the products of science are contextually specific constructions [and] bear the mark of the situational contingency and interest structure of the process by which they are generated" (Knorr-Cetina, 1981, p. 5). Social constructivism was, in part, a reaction against Merton's (1957; 1967) normative/functionalist model of science and the Mertonian tenet that external social factors influence scientists and how they interact, but are irrelevant to knowledge produced by science.

In the field of information science however, there has been ample discussion as to what actually constitutes an Information Use Environment. Rosenbaum (1993; 1996) and Taylor (1986; 1991) are two of the most important leaders in this discussion. Taylor's (1986) value-added theory asserts that the Information Use Environment (IUE) is a space where information related behaviours occur and that such behaviours constitute "the sum of activities through which information becomes useful" (p. 221). The IUE may be defined as "the set of those elements that a) affect the flow and use of information messages into, within, and out of any definable entity; and b) determine the criteria by which the value of information messages will be judged" (Taylor, 1986, pp. 3-4). To fully understand the IUE, or any IUE, Taylor (1991) proposes that it is important to collect data concerning the following elements: sets of people, the structure of their problems, typical settings and the resolution of problems.

Rosenbaum's (1996) critique of Taylor's IUE is that it is "fundamentally ambiguous" and that much of what is emphasized in his theory creates a tension between "perspectives based on structural assumptions and those based on action-oriented assumptions" (1996, p. 71). Consequently, Rosenbaum argues for a structurational approach to the IUE, which combines both Taylor's value-added theory with Gidden's (1984) theory of structuration. With this new structurational approach, the duality of structure is given precedence so that the two main constructs of Taylor's original dichotomy – the IUE and information-related behaviours – form an interrelationship. The IUE is "instantiated in action" and "routinely produced and reproduced through the social practices or information behaviour of users" (Rosenbaum, 1996, p. 112). Similarly, information behaviours can "certainly be constrained, shaped, and enabled by the IUE" (p. 112). Essentially "the presence of each other makes the other possible; neither has meaning without the other" (1996, p. 112).

In this paper, Rosenbaum's (1996) structurational perspective of the IUE is embraced: it combines the best of Giddens and Taylor, and fits very well with the proposed invisible college model. With respect to his view, let us consider again the case of Singularity Theory research as an invisible college. In mathematics, the international mathematics research institute constitutes what we may call a critical IUE. Mathematicians as social actors have created a need for specialized research institutes: their collegial activities over the years have "instantiated in action" the existence of this type of environment. Likewise, the international mathematics research institute, as an equal participant in a bi-directional or dual relationship, has the power to shape and influence the mathematicians' social experience of sharing and doing research.

The international mathematics research institute is a relatively new IUE for fostering invisible college activity. Many of the institutes operating today, including the Isaac Newton

Institute in Cambridge, England, the Fields Institute in Toronto, Canada, and the Mathematical Sciences Research Institute in Berkeley, California have only just been established in the 1980s and early 1990s. Since their development, mathematicians from around the world have had more significant opportunities for collegial interaction. The institutes have in effect transformed the loner "gentlemen's tradition" of doing mathematics into a highly "professionalized" discipline.

Mathematicians are invited by the institute scientific steering committees to propose and organize programs around a specific subject, usually a mature subject, so that work may be done to re-vitalize the area. Every program proposal explains how a series of seminars, workshops affiliated with the program might further the subjects' goals, for instance, by inspiring colleagues to focus on new applications and/or develop interactions with other complementary subjects. Usually the activities corresponding to the goals are somewhat formal (e.g., organized workshops), but they are designed overall to get the mathematicians talking, thinking, discussing and collaborating. Since the mathematicians cannot stay at any one institute forever the hope is that after they visit, they will take new ideas away with them and work on intellectual construction beyond the programmed situation.

Consider now the ACA-Social network map *of Singularity Theory and Its Applications to Quantum Field Theory* presented in Figure 7. Here we see how the Isaac Newton Institute as a critical IUE has been used to enhance the research goals of Singularity Theory by encouraging interaction with another complementary research area known as Quantum Field Theory. Over time a new invisible college network may emerge, although at this point it is difficult to say. In mathematics however, invisible college networks are inclined to grow over time through the process of intellectual "bridge-building." Simon Singh (1997), author of *Fermat's Enigma: The Epic Quest to Solve the World's Greatest Mathematical Problem* observes the enormous "value of mathematical bridges…They enable communities of mathematicians who have been living on separate islands…to explore each other's creations" (p. 191).

A specialized research institute, like the Isaac Newton Institute, is just one example of an IUE; hence the IUE as a general construct is open for further consideration. Scientists as social actors work together in different types of IUEs; therefore, the IUE is above all else "the set of elements that affect the flow and use of information messages into, within, and out of any definable entity" (Taylor, 1986, p. 3). Any definable entity within the invisible college model could be an e-mail-based IUE or perhaps a special electronic "collaboratory" or Virtual Institute Network (VIN) designed for use on the Web. Lievrouw and Carley (1990) focus on the increase in the amount of interpersonal interaction facilitated by 'telescience' (NASA's term for the new electronic infrastructure for scientific communication); hence, it is reasonable to speculate how electronic research environments might create a departure from what Price (1963) or Crane (1972) observed with invisible colleges years ago. This paper concerning Singularity Theory does not provide an in-depth focus on electronic environments; however we know that Virtual Institute Networks (VINS) are designed to be much more interactive than e-mail; they allow mathematicians (and other scientists) who rely on graphs, or figures to convey abstract ideas to communicate with one another as though they were meeting face to face.[5]

[5] Braham's (1995) version of the VIN interface talks to a Virtual Internet Server (a modified IRC server with new protocols) and is set up to appear as a sophisticated blackboard. A VIN user may load images and everybody tuned into the network will see the image. Scientists may write on the image, type text on the blackboard, erase the blackboard, change the colors of lines and texts, move between channels, create new channels, find out who else is on the channel, browse the World Wide Web and use a chat function to engage in discussion.

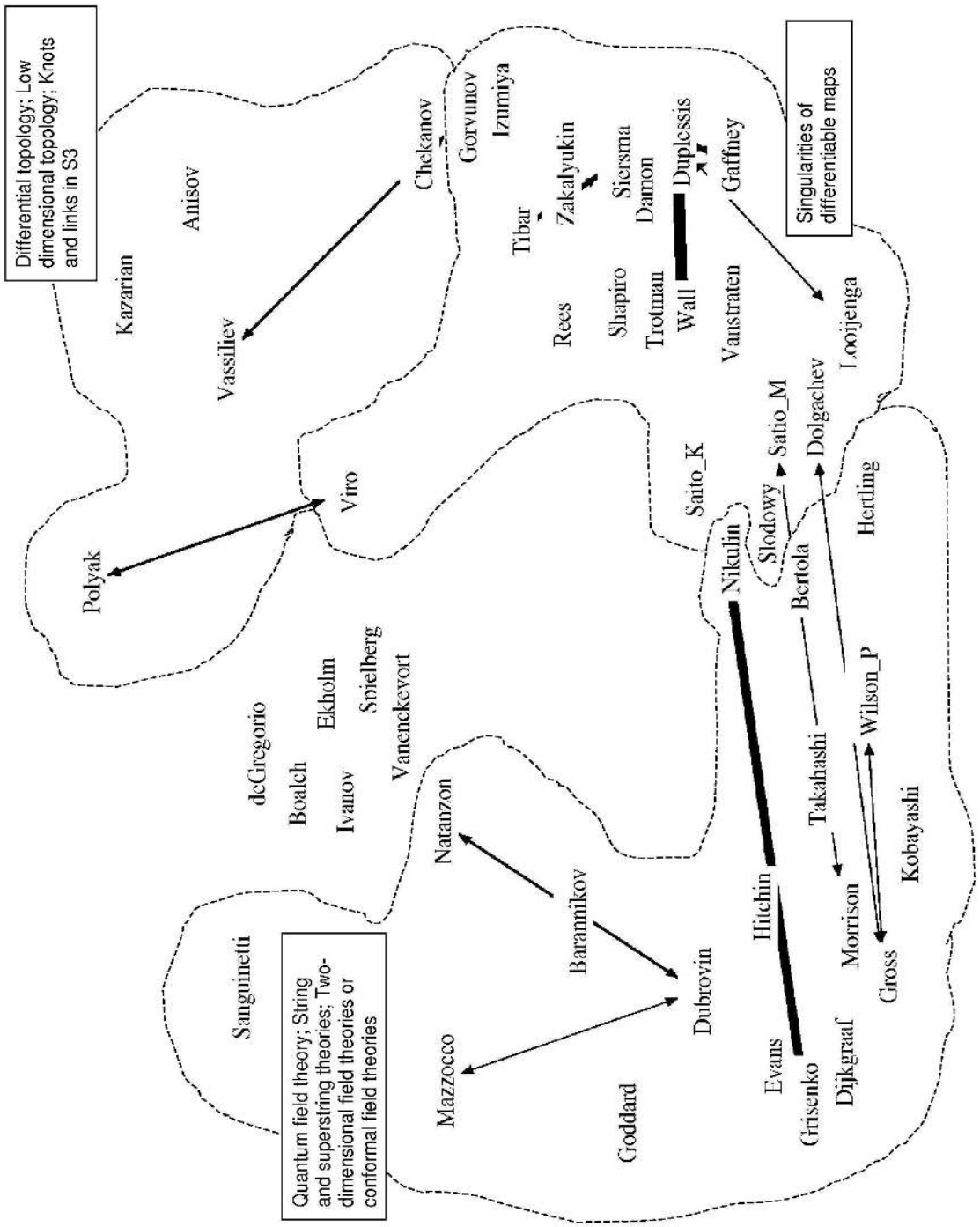

Figure 7. ACA-Social Network map of the Isaac Newton Institute Workshop (2000) on *Singularity Theory and Its Applications to Quantum Field Theory*.

If the VIN becomes commonplace, then further research will be needed to understand its social and scientific impact. Will scientists make use of VINs like they use current international research institutes? What effect will the VIN have on research output, peer review or the collective egos of scientists? Will scientists spend less time traveling and more time writing for publication? Will they become more interested in sharing ideas, more competitive or less competitive, or, more trusting or less trusting of one another? What effect will the VIN have on scientists coming from less technologically advanced societies? Brunn and O'Lear (1999) suggest that certain social consequences are likely to deepen "between … members of the 'electronic invisible college' versus those who cannot and choose not to participate. Exclusion may be based on the inability or unwillingness on the part of the individual or the state to invest in those technologies…" (p. 299).

Finally, if the researcher wishes to understand how an IUE supports invisible college activity, fieldwork is once again essential. All parts of the fieldwork must be considered carefully, including the process of gaining entry to the chosen setting, earning the trust of individuals who will be observed or interviewed, and adhering to ethical standards for conducting qualitative research. Of interest to the researcher during the fieldwork situation should be answers to the following questions: *What types of resources are available to the scientists who visit or participate in the IUE? How does the IUE shape social interaction? How does the IUE constrain social interaction? How do the scientists' as social actors make use of the IUE for information sharing and/or research and what are their personal expectations and experiences?*

Conclusion

Invisible colleges have been examined frequently in past years and despite a lack of consensus regarding an invisible college definition, this phenomenon definitely exists and will continue to exist in our increasingly global society. If we are to continue studying invisible colleges, we should consider adopting a shared perspective, or agree at least upon a systematic approach for data analysis, giving full attention to their primary components. To assist in this systematic approach, researchers are invited to use the new research model, shown in Figure 2 termed the "structurationally informed value-added model for the study of scientific organizations, (i.e., invisible colleges)" (see Figure 2). This new model demonstrates clearly that an invisible college is multifaceted and that it results from an interrelationship of *subject specialty*, *social actors* and *Information Use Environment (IUE)*. Each component presents a challenge to the researcher in terms of a need for using a "toolkit" of complementary research techniques to highlight the interrelationship. Microbiologists need microscopes as tools to observe and understand the properties of (otherwise invisible) bacteria; therefore, we need our own tools to help make the invisible college more visible for in-depth analysis and understanding. In the future, researchers who make use of the proposed model can look for new opportunities to compare invisible colleges. All invisible colleges are basically alike, but will possess a unique lifecycle depending on how they align themselves with different subjects, social actors and IUEs. The strength or weakness of each component is the factor that may assist researchers in determining why it is that some invisible colleges emerge, thrive, decline or altogether disappear more or less rapidly over time. *Did the specialty area lack important problems? Did the social actors cease to involve themselves in activities that would allow them to share new information, including new research ideas, or simply migrate to other areas of*

research? Was the invisible college not situated within a supportive IUE ? All information that is gathered in relation to these questions can eventually help policy-makers focus on the type of programs needed to assist invisible colleges in their knowledge development purpose.

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