INTERNET

Could the Internet Balkanize Science?

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Working with information requires time and attention. A wealth of information leads to a poverty of attention, so attention must be allocated efficiently. Depending on how this task is managed, the Internet could lead to the fragmentation of research—a balkanization of the global village.

The online information explosion makes explicit searching and filtering not only possible but necessary. Automated agents scan the Web using declared preferences while collaborative filters master new ones, by comparing hundreds of thousands of user profiles, to make strikingly accurate suggestions on items of potential interest. Highly customized online journals, with a subscriber base of one, have become feasible.

Organizational structures are also changing. Plummeting costs of information technology have changed the relative efficiency of different structures for coordinating work in firms and markets (*1*) and in universities (*2*). Although most research (and press attention) has focused on business restructuring, the structure of scientific inquiry is not immune to a changing technological environment. In particular, the unifying and integrating benefits of access technology should not be taken for granted. We find that greater access to resources can increase scientific productivity but that insularity might also rise (*3*). Faced with a wealth of resources and limited attention, researchers can focus on only those articles and colleagues that really interest them, regardless of location, and effectively exclude others.

The proof of Fermat's last theorem offers an illustration. Discovery of a glitch in the proof sparked an electronic exchange of ideas among internationally distributed algebraic topologists. This led the author, Andrew Wiles, to strengthen his ideas and fix the proof. Focused interactions enhanced productivity within this mathematical subspecialty, even as its members turned from other tasks in their efforts to be among the first to find answers.

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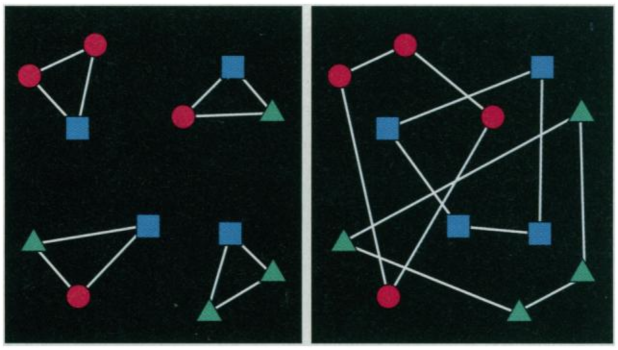
Scientists who use information technology appear to be more productive: they reportedly write more papers, earn greater peer recognition, and know more colleagues (*4*). "Collaboratories" provide new ways to coordinate large-scale research projects and to access remote data and research specialists (*5*). This evidence supports the promise of the World Wide Web to build broader, richer scientific communities.

Yet, if information technology helps an algebraic topologist in North America spend more time interacting with colleagues globally, what happens to his or her interactions with the computer scientist, the biologist, or the graduate student down the hall? As quickly as information technology collapses barriers based on geography, it forces us to build new ones based on interest or time. Ironically, global communication networks can leave intact or even promote partitions based on specialty, politics, or perceived rank, divisions that can matter far more than geography.



Balkanization grows. Information technology can reconstitute geographic communities (shape locations in left panel) by research discipline (shape colors in right panel).

Kuhn identified the widening gulf between scientific specialists more than three decades ago (*6*). The power of emerging information technology to search, connect, screen, and select can exacerbate this problem. The same information lens that brings distant colleagues into focus can inadvertently produce tunnel vision and peripheral blindness. Geographic balkanization, which separates scientists in physical space, can give way to electronic balkanization, which separates them in "topic space," as they trade local for long-distance connections with greater relevance by interest group (see figure).

These interactions have been modeled formally (*3*). As one index of "balkanization," we can define β to depend on the number of topics and the number of community members aware of each topic. If community members $M(t)$ have access to topics $t \in \{1, 2, \ldots T\}$ then let

$$\beta = 1 - \frac{1}{T}\frac{1}{T-1}\sum_{t}^{T}\sum_{s \neq t}^{T}\frac{|M(t) \cap M(s)|^2}{|M(t)||M(s)|}$$

In the figure, β rises from 0.35 to 1 as intergroup interaction declines. More general mathematical models reveal that this and other metrics of balkanization can increase as technology improves searching, filtering, and long-distance collaboration.

As technology improves, individual preferences largely determine whether balkanization increases or decreases. If scientists prefer more focused interaction than is available locally, an increase in information technology will lead to narrower scientific interactions. Because the Internet makes it easier to find more interesting contacts, those less interesting contacts near the threshold of attention may be abandoned. Unless scientists actively seek diversity, global access might therefore balkanize interactions.

Focus is a response to the poverty of attention. When daily interactions bombard us with irrelevant information, a strong desire to focus might evolve as a useful heuristic for minimizing distractions. By radically improving filtering, however, advanced information technology can lead this same heuristic to inordinately favor depth at too great a cost in breadth. Old strategies can become counterproductive in new environments.

A second form of focus is also needed: an emphasis on perceived quality. The Web accumulates 200,000 new pages daily, along with thousands of postings to public discussion groups, a wealth of information that creates a need to sort the diamonds from the dust. To preserve the caliber of interaction, most prominent scientists retreat to small, private e-mail lists and invited discussion groups (*7*). The recently announced Platform for Internet Content Selection will not only enable the labeling of material in online journals ("seminal article"), but the creators foresee "labels for Usenet authors according to the quality of the messages they post: posts from those with poor reputations could be screened out" [(*8*), p. 93]. Communications that once depended on geography, proximity, and serendipity are screened and filtered for perceived relevance and reputation. Stratification as well as balkanization can result.

Science advances not just from publication but from dialogue, apprenticeship, and collaboration. Although we commonly think of scientific knowledge as a public good—available at zero cost once it has been produced—the specialized skills, education, and foreknowledge needed to use it imply that scientific information is far from free. Incentives are necessary to encourage creation, distribution, and use.

The incentives faced by individual scientists, however, do not automatically encourage them to maximize scientific progress. For example, overspecialization can be privately beneficial while erecting virtual walls between scholarly communities. If intradisciplinary interactions substitute for interdisciplinary ones, then the intellectual cross-pollination of ideas can suffer. Consider that the Black-Scholes equation for pricing financial options is derived from an arbitrage model related to the heat transfer equation (9). Conceivably, reducing the spillovers between thermodynamics and finance could have forestalled the development of options markets. Similarly, Crick's training in physics and Watson's background in zoology helped them develop their theories of DNA (10). In general, the insularity of subpopulations negatively affects the speed at which new ideas percolate through an entire population (11).

Balkanization can be avoided. A scientist may use information technology to select diverse contacts as easily as specialized contacts. Integration or fragmentation hinges on individual preferences and factors such as whether the pressure to publish at the frontier of one's own discipline is low enough to permit time for exploration in others.

New technologies give us new options to consider. They enable both the global village and the virtual Balkans of scientific collaboration. Although no single scenario is inevitable, certain outcomes, once achieved, can be difficult to reverse. At this early stage, we can, and should, explicitly consider what we value as we shape the nature of our networks, with no illusions that a greater sense of community will inexorably result.

References

1. T. W. Malone and J. F. Rockart, *Sci. Am.* **265**, 128 (September 1991).
2. E. M. Noam, *Science* **270**, 247 (1995).
3. M. Van Alstyne and E. Brynjolfsson, *Proceedings of the International Conference on Information Systems*, Cleveland, OH (1996). More detailed modeling information is also available on the Web at http://web.mit.edu/marshall/www/InfoAccess.html
4. B. Hesse, L. Sproull, S. Kiesler, J. Walsh, *Commun. ACM* **36**, 90 (1993).
5. W. A. Wulf, *Science* **261**, 854 (1993).
6. T. Kuhn, *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago, ed. 2, 1970).
7. J. Chao, "Internet Pioneers Abandon World They Created," *Wall Street Journal*, 7 June 1995, p. B8; S. Steinberg, *Technol. Rev.* **97**, 25 (1994).
8. P. Resnick and J. Miller, *Commun. ACM* **39**, 87 (1996).
9. F. Black and M. Scholes, *J. Polit. Econ.* **81**, 637 (1973).
10. A. S. Moffat, *Science* **259**, 1253 (1993).
11. P. A. David and D. Foray, in *Global Telecommunications Strategies and Technical Change*, G. Pogorel, Ed. (Elsevier, Amsterdam, 1993).

ASTROCHEMISTRY

Space Carbon: Neutral Pathways?

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The discovery of complex molecules in interstellar space in the late 1960s by Townes, Welch, and their collaborators (1) destroyed the conventional wisdom of the day and created widespread interest in the chemistry of interstellar dust clouds. On page 1508 of this issue, Kaiser *et al.* (2) heighten this interest by providing evidence that a new class of reactions—reactions between certain charge neutral precursors—may be a critical component of this chemistry.

In the 1960s it was recognized that self-shielding of dense (10^3 to 10^6 cm^{-3}) clouds against interstellar ultraviolet radiation permits a rich and complex chemistry to pervade these objects, but the mechanism for the formation of molecules at the ultralow cloud temperatures ($T < 50$ K) remained an enigma. This dilemma was solved in the mid-1970s by Herbst and Klemperer (3), who proposed a scheme of ion-molecule reactions, known to often possess nearly zero activation barriers, that nicely accounted for the principal observations. After the detection in dense clouds of two molecular ions, HCO^+ and HNN^+, by Snyder (4) and Thaddeus and collaborators (5), respectively, and the confirmation of these observations by microwave spectroscopy in the laboratory of Woods (6), a scheme featuring ion-molecule reactions driven by cosmic ray ionization of hydrogen followed by ion-electron dissociative recombination reactions became the paradigm for the chemistry of interstellar dust clouds. Furthermore, it became recognized that molecules were intimately involved as cooling agents in the critical processes of star formation and gravitational collapse of these objects.

More recent observations have made it clear that this picture is, however, incomplete. The detection of long-chain carbon-containing molecules like HC_5N in dark dust clouds by Avery and co-workers (7) revealed a class of molecules, the high abundance of which was not readily explained by the ion-molecule scheme. The discovery of larger interstellar molecules ($HC_{11}N$, for example) along with pure-carbon-chain species like C_3 and C_5 (8) in circumstellar shells of dying carbon stars and possibly in cold clouds (9) likewise implied that another type of chemistry must be occurring, at least under some conditions. The tentative association of polycyclic aromatic hydrocarbon molecules with the endemic unidentified interstellar emission bands may constitute still another example (10). In summary, it now seems that much of the carbon chemistry of interstellar dust clouds is not readily explained within the context of the ion-molecule reaction scheme. This is a problem of considerable significance because carbon is the fourth most abundant element, is the critical element for life as we know it, and is most likely to be crucially involved in the nucleation of solid matter from the gaseous state.

Until very recently, reactions between neutral species have not been considered relevant to interstellar cloud chemistry (except for the formation of molecular hydrogen, which is thought to occur on dust grain surfaces). Neutral-neutral reactions are typically characterized by much higher activation barriers and lower cross sections than are ion-molecule processes. Recent studies, however, have indicated that several classes of neutral-neutral reactions may actually be very important (11). Husain's group has found that carbon atoms can insert into unsaturated carbon molecules (such as acetylene) with no activation barriers and high probability (12). It was quickly recognized that such reactions could provide a route for synthesizing many of the interstellar molecules that were not well explained by the ion-molecule chemistry. However, the incorporation of such neutral-neutral reactions into the complicated models for interstellar dust cloud chemistry leads to contradictions: neutral-neutral reactions tend to produce stable small molecules quite early in the chemical process, thus terminating molecular growth and limiting the number of complex molecules that are produced (13).

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