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**REPORTS**

**Empirical Analysis of an Evolving Social Network**

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Social networks evolve over time, driven by the shared activitiesand affiliations of their members, by similarity of individuals'attributes, and by the closure of short network cycles. We analyzeda dynamic social network comprising 43,553 students, faculty,and staff at a large university, in which interactions betweenindividuals are inferred from time-stamped e-mail headers recordedover one academic year and are matched with affiliations andattributes. We found that network evolution is dominated bya combination of effects arising from network topology itselfand the organizational structure in which the network is embedded.In the absence of global perturbations, average network propertiesappear to approach an equilibrium state, whereas individualproperties are unstable.

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Social networks have attracted great interest in recent years,largely because of their likely relevance to various socialprocesses, such as information processing ([*1*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF1)), distributed search([*2*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF2)), and diffusion of social influence ([*3*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF3)). For many years,however, social scientists have also been interested in socialnetworks as dynamic processes in themselves ([*4*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF4)): Over time,individuals create and deactivate social ties, thereby alteringthe structure of the networks in which they participate. Socialnetwork formation is a complex process in which many individualssimultaneously attempt to satisfy their goals under multiple,possibly conflicting, constraints. For example, individualsoften interact with others similar to themselves—a tendencyknown as homophily ([*5*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF5), [*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6))—and attempt to avoid conflictingrelationships ([*7*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF7), [*8*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF8)) while exploiting cross-cutting circlesof acquaintances ([*9*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF9)). However, the realization of these intentionsis subject to spatial and social proximity of available others([*9*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF9), [*10*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF10)). In circumstances where individuals may benefit fromcooperative relationships, they may emphasize embedded ties—thosebelonging to locally dense clusters ([*11*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF11)). For example, theymay choose new acquaintances who are friends of friends—aprocess known as triadic closure ([*12*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF12)). They may, however, alsoseek access to novel information and resources and hence benefitfrom access to bridges ([*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13))—connections outside theircircle of acquaintances—or by spanning structural holes([*14*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF14)) precisely between others who do not know one another. Finally,social ties may dissolve for various reasons, such as when theyare not supported by other relations ([*15*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF15)), or else conflictwith them ([*16*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF16)).

To what extent each of these individually plausible mechanismsmanifests itself in various social and organizational contextsis largely an empirical matter, requiring longitudinal (i.e.,collected over time) network data ([*4*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF4)) combined with informationabout individuals' attributes and group affiliations ([*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6), [*10*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF10),[*17*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF17)). Yet longitudinal network data are rare, and the best knownexamples are for small groups ([*4*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF4), [*18*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF18)). Recent studies of muchlarger networks, by contrast, have tended to focus on cross-sectional(i.e., static) analysis ([*19*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF19), [*20*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF20)), or they have emphasized eitherthe interactions between individuals ([*21*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF21), [*22*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF22)) or their groupaffiliations ([*17*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF17)), but not both.

We analyzed a longitudinal network data set created by mergingthree distinct but related data structures. First, we compileda registry of e-mail interactions in a population of 43,553undergraduate and graduate students, faculty, and staff of alarge university over the course of one academic year. For eache-mail message, the timestamp, sender, and list of recipients(but not the content) were recorded. Second, for the same population,we gathered information specifying a range of personal attributes(status, gender, age, departmental affiliation, and number ofyears in the community). Third, we obtained complete lists ofthe classes attended and taught, respectively, by students andinstructors in each semester. For privacy protection, all individualand group identifiers were encrypted; we can determine, forexample, whether two individuals were in the same class togetherbut not which class that was. Because in a university settingclass attendance provides essential opportunities for face-to-faceinteraction (at least for students), we used classes to representthe changing affiliation structure.

Our use of e-mail communication to infer the underlying networkof social ties is supported by recent studies reporting thatuse of e-mail in local social circles is strongly correlatedwith face-to-face and telephone interactions ([*23*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF23), [*24*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF24)). Individualsand groups of individuals may differ in their e-mail usage;thus, inferences drawn on a small sample of communicating pairsmay be confounded by the idiosyncrasies of particular personalitiesand relationships. However, by averaging over thousands of suchrelationships, we expect that our results will represent onlythe most general regularities (at least within the environmentof a university community) governing the initiation and progressionof interpersonal communication. To ensure that our data do indeedreflect interpersonal communication as opposed to ad hoc mailinglists and other mass mailings, we filtered out messages withmore than four recipients (95% of all messages had four or feweraddressees). After filtering, there were 14,584,423 messagesexchanged by the users during 355 days of observation.

Ongoing social relationships produce spikes of e-mail exchangethat can be observed and counted ([*20*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF20), [*21*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF21)). The stronger therelationship between two individuals, the more spikes will beobserved for this particular pair, on average, within a giventime interval. We approximate instantaneous strength *wij* ofa relationship between two individuals *i* and*j* by the geometricrate of bilateral e-mail exchange within a window of {tau} = 60 days([*25*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF25)). The instantaneous network at any point in time includesall pairs of individuals that sent one or more messages in eachdirection during the past 60 days. Using daily network approximations,we calculated (i) shortest path length *dij* and (ii) the numberof shared affiliations *sij* for all pairs of individuals in thenetwork on 210 consecutive days spanning most of the fall andspring semesters ([*25*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF25)). By identifying new ties that appear inthe network over time, we can compute two sets of measures:(i) cyclic closure and (ii) focal closure biases. For some specifiedvalue of *dij*, cyclic closure bias is defined as the empiricalprobability that two previously unconnected individuals whoare distance *dij* apart in the network will initiate a new tie.Thus cyclic closure naturally generalizes the notion of triadicclosure ([*12*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF12)), i.e., formation of cycles of length three. Byanalogy, we define focal closure bias as the empirical probabilitythat two strangers who share an interaction focus (in the presentcase, a class) will form a new tie. Because class attendanceis relevant mostly for students, the results on focal and cyclicclosure are presented here for a subset of 22,611 graduate andundergraduate students ([*25*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF25)).

[Figure 1A](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG1) (triangles) shows that in the absence of a sharedfocus (i.e., class), cyclic closure diminishes rapidly in strengthwith *dij*, implying that individuals who are far apart in thenetwork have no opportunity to interact and hence are very unlikelyto form ties. For example, individuals who are separated bytwo intermediaries (*dij* = 3) are about 30 times less likelyto initiate a new tie than individuals who are separated byonly one intermediary (*dij* = 2). [Figure 1A](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG1)(circles), however,demonstrates that when two individuals share at least one class,they are on average 3 times more likely to interact if theyalso share an acquaintance (*dij* = 2), and about 140 times morelikely if they do not (*dij* > 2). In addition, [Fig. 1B](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG1) showsthat the empirical probability of tie formation increases withthe number of mutual acquaintances both for pairs with (circles)and without (triangles) shared classes, becoming independentof shared affiliations for large numbers of mutual acquaintances(six and more). [Figure 1C](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG1) displays equivalent information forshared classes, indicating that while the effect of a singleshared class is roughly interchangeable with a single mutualacquaintance, the presence of additional acquaintances has agreater effect than additional foci in our data set. These findingsimply that even a minimally accurate, generative network modelwould need to account separately for (i) triadic closure, (ii)focal closure, and (iii) the compounding effect of both biasestogether.

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| |  |  | | --- | --- | |  | **Fig. 1.** Cyclic and focal closure. (**A**) Average daily empirical probability *p*new of a new tie between two individuals as a function of their network distance *dij*. Circles, pairs that share one or more interaction foci (attend one or more classes together); triangles, pairs that do not share classes. (**B**) *p*new as a function of the number of mutual acquaintances. Circles, pairs with one or more shared foci; triangles, pairs without shared foci. (**C**) *p*new as a function of the number of shared interaction foci. Circles, pairs with one or more mutual acquaintances; triangles, pairs without mutual acquaintances. Lines are shown as a guide for the eye; standard errors are smaller than symbol size. [[View Larger Version of this Image (22K GIF file)]](http://www.sciencemag.org/cgi/content/full/311/5757/88/FIG1) | |

Our data can also shed light on theoretical notions of tie strength([*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13)) and attribute-based homophily ([*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6), [*26*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF26)). We found ([Fig. 2](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG2))that the likelihood of triadic closure increases if the averagetie strength between two strangers and their mutual acquaintancesis high, which supports commonly accepted theory ([*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6), [*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13)). Bycontrast, homophily with respect to individual attributes appearsto play a weaker role than might be expected. Of the attributeswe considered in this and other models ([*27*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF27))—status (undergraduate,graduate student, faculty, or staff), gender, age, and timein the community—none has a significant effect on triadicclosure. The significant predictors are tie strength, numberof mutual acquaintances, shared classes, the interaction ofshared classes and acquaintances, and status obstruction, whichwe define as the effect on triadic closure of a mediating individualwho has a different status than either of the potential acquaintances.For example, two students connected through a professor areless likely to form a direct tie than two students connectedthrough another student, ceteris paribus. We suspect, however,that status obstruction may be an indicator of unobserved focalclosure beyond class attendance. Thus, although homophily hasoften been observed with respect to individual attributes incross-sectional data ([*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6), [*26*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF26)), these effects may be mostly indirect,operating through the structural constraint of shared foci ([*10*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF10)),such as selection of courses or extracurricular activities.

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| |  |  | | --- | --- | |  | **Fig. 2.** Results of multivariate survival analysis of triadic closure for a sample of 1190 pairs of graduate and undergraduate students. Shown are the hazard ratios and 95% confidence intervals from Cox regression of time to tie formation between two individuals since their transition to distance *dij* = 2. Hazard ratio *g* means that the probability of closure changes by a factor of *g* with a unit change in the covariate or relative to the reference category. We treat a covariance as significant if the corresponding 95% confidence interval does not contain *g* = 1 (no effect). Predictors, sorted by effect magnitude: strong indirect (1 if indirect connection strength is above sample median, 0 otherwise), classes (number of shared classes), acquaintances (number of mutual network neighbors less 1), same age (1 if absolute difference in age is less than 1 year, 0 otherwise), same year (1 if absolute difference in number of years at the university is less than 1, 0 otherwise), gender [effects of male-male (MM) and female-female (FF) pair, respectively, relative to a female-male (FM) pair], acquaint\*classes (interaction effect between acquaintances and classes), and obstruction (1 if no mutual acquaintance has the same status as either member of the pair, 0 otherwise) ([*25*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF25)). [[View Larger Version of this Image (17K GIF file)]](http://www.sciencemag.org/cgi/content/full/311/5757/88/FIG2) | |

Our results also have implications for the utility of cross-sectionalnetwork analysis, which relies on the assumption that the networkproperties of interest are in equilibrium ([*4*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF4)). [Figure 3](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG3) showsthat different network measures exhibit varying levels of stabilityover time and with respect to the smoothing window {tau}. Averagevertex degree <*k* >, fractional size of the largest component *S*,and mean shortest path length *L* all exhibit seasonal changesand produce different measurements for different choices of{tau}, where <*k* > is especially sensitive to {tau}. The clustering coefficient*C* ([*28*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF28)), however, stays virtually constant as <*k* > changes, suggesting,perhaps surprisingly, that averages of local network propertiesare more stable than global properties such as *L* or *S*. Nevertheless,these results suggest that as long as the smoothing window {tau}is chosen appropriately and care is taken to avoid collectingdata in the vicinity of exogenous changes (e.g., end of semester),average network measures remain stable over time and thus canbe recovered with reasonable fidelity from network snapshots.

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| |  |  | | --- | --- | |  | **Fig. 3.** Network-level properties over time, for three choices of smoothing window {tau} = 30 days (dashes), 60 days (solid lines), and 90 days (dots). (**A**) Mean vertex degree <*k* >. (**B**) Fractional size of the largest component *S*. (**C**) Mean shortest path length in the largest component *L*. **(D)** Clustering coefficient *C*. [[View Larger Version of this Image (32K GIF file)]](http://www.sciencemag.org/cgi/content/full/311/5757/88/FIG3) | |

The relative stability of average network properties, however,does not imply equivalent stability of individual network properties,for which the empirical picture is more complicated. On theone hand, we find that distributions of individual-level propertiesare stable, with the same caveats that apply to averages. Forexample ([Fig. 4, A to C](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG4)), the shape of the degree distribution*p*(*k*) is relatively constant across the duration of our dataset except during natural spells of reduced activity, such aswinter break ([Fig. 4C](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG4)). On the other hand, as [Fig. 4D](http://www.sciencemag.org/cgi/content/full/311/5757/88#FIG4) illustrates,individual ranks change substantially over the duration of thedata set. Analogous results ([*27*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF27)) apply to the concept of "weakties" ([*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13)): The distribution of tie strength in the networkis stable over time, and bridges are, on average, weaker thanembedded ties [consistent with ([*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13))]. However, they do not retaintheir bridging function, or even remain weak, indefinitely.

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| |  |  | | --- | --- | |  | **Fig. 4.** Stability of degree distribution and individual degree ranks. (**A**) Degree distribution in the instantaneous network at day 61, logarithmically binned. (**B**) Same at day 270. (**C**) The Kolmogorov-Smirnov statistic *D* comparing degree distribution in the instantaneous network at day 61 and in subsequent daily approximations. **(D)**Dissimilarity coefficient for degree ranks {zeta} = 1 – rS2, where rS is the Spearman rank correlation between individual degrees at day 61 and in subsequent approximations. {zeta} varies between 0 and 1 and measures the proportion of variance in degree ranks that cannot be predicted from the ranks in the initial network. [[View Larger Version of this Image (21K GIF file)]](http://www.sciencemag.org/cgi/content/full/311/5757/88/FIG4) | |

Our results suggest that conclusions relating differences inoutcome measures such as status or performance to differencesin individual network position ([*14*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF14)) should be treated with caution.Bridges, for example, may indeed facilitate diffusion of informationacross entire communities ([*13*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF13)). However, their unstable naturesuggests that they are not "owned" by particular individualsindefinitely; thus, whatever advantages they confer are alsotemporary. Furthermore, it is unclear to what extent individualsare capable of strategically manipulating their positions ina large network, even if that is their intention ([*14*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF14)). Rather,it appears that individual-level decisions tend to "averageout," yielding regularities that are simple functions of physicaland social proximity. Sharing focal activities ([*10*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF10)) and peers(*[26](http://www.sciencemag.org/cgi/content/full/311/5757/88" \l "REF26)*), for example, greatly increases the likelihood of individualsbecoming connected, especially when these conditions apply simultaneously.

It may be the case, of course, that the individuals in our population—mostlystudents and faculty—do not strategically manipulate theirnetworks because they do not need to, not because it is impossible.Thus, our conclusions regarding the relation between local andglobal network dynamics may be specific to the particular environmentthat we have studied. Comparative studies of corporate or militarynetworks could help illuminate which features of network evolutionare generic and which are specific to the cultural, organizational,and institutional context in question. We note that the methodswe introduced here are generic and may be applied easily toa variety of other settings. We conclude by emphasizing thatunderstanding tie formation and related processes in socialnetworks requires longitudinal data on both social interactionsand shared affiliations ([*4*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF4), [*6*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF6), [*10*](http://www.sciencemag.org/cgi/content/full/311/5757/88#REF10)). With the appropriate datasets, theoretical conjectures can be tested directly, and conclusionspreviously based on cross-sectional data can be validated orqualified appropriately.

**References and Notes**

* 1. P. S. Dodds, D. J. Watts, C. F. Sabel, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 12516 (2003).[[Abstract/Free Full Text]](http://www.sciencemag.org/cgi/ijlink?linkType=ABST&journalCode=pnas&resid=100/21/12516)
* 2. J. M. Kleinberg, *Nature* **406**, 845 (2000).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1038%2F35022643&link_type=DOI)[[Medline]](http://www.sciencemag.org/cgi/external_ref?access_num=10972276&link_type=MED)
* 3. T. W. Valente, *Network Models of the Diffusion of Innovations* (Hampton Press, Cresskill, NJ, 1995).
* 4. P. Doreian, F. N. Stokman, Eds., *Evolution of Social Networks* (Gordon and Breach, New York, 1997).
* 5. P. Lazarsfeld, R. Merton, in *Freedom and Control in Modern Society*, M. Berger, T. Abel, C. Page, Eds. (Van Nostrand, New York, 1954), pp. 18–66.
* 6. M. McPherson, L. Smith-Lovin, J. M. Cook, *Annu. Rev. Sociol.* **27**, 415 (2001).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1146%2Fannurev.soc.27.1.415&link_type=DOI)[[Web of Science]](http://www.sciencemag.org/cgi/external_ref?access_num=000170748100017&link_type=ISI)
* 7. J. A. Davis, *Am. J. Sociology* **68**, 444 (1963).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1086%2F223401&link_type=DOI)
* 8. T. M. Newcomb, *The Acquaintance Process* (Holt Rinehart and Winston, New York, 1961).
* 9. P. M. Blau, J. E. Schwartz, *Crosscutting Social Circles* (Academic Press, Orlando, FL, 1984).
* 10. S. L. Feld, *Am. J. Sociology* **86**, 1015 (1981).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1086%2F227352&link_type=DOI)
* 11. J. S. Coleman, *Sociol. Theory* **6**, 52 (1988).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.2307%2F201913&link_type=DOI)
* 12. A. Rapoport, *Bull. Math. Biophys.* **15**, 523 (1953).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1007%2FBF02476440&link_type=DOI)
* 13. M. S. Granovetter, *Am. J. Sociology* **78**, 1360 (1973).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1086%2F225469&link_type=DOI)
* 14. R. S. Burt, *Am. J. Sociology* **110**, 349 (2004).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1086%2F421787&link_type=DOI)
* 15. M. Hammer, *Soc. Networks* **2**, 165 (1980).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1016%2F0378-8733%2879%2990005-4&link_type=DOI)[[Web of Science]](http://www.sciencemag.org/cgi/external_ref?access_num=A1980JT13300005&link_type=ISI)
* 16. M. T. Hallinan, E. E. Hutchins, *Soc. Forces* **59**, 225 (1980).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.2307%2F2577842&link_type=DOI)[[Web of Science]](http://www.sciencemag.org/cgi/external_ref?access_num=A1980KH60000013&link_type=ISI)
* 17. M. E. J. Newman, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 404 (2001).[[Abstract/Free Full Text]](http://www.sciencemag.org/cgi/ijlink?linkType=ABST&journalCode=pnas&resid=98/2/404)
* 18. S. Wasserman, K. Faust, *Social Network Analysis: Methods and Applications* (Cambridge Univ. Press, Cambridge, 1994).
* 19. M. E. J. Newman, *SIAM Review* **45**, 167 (2003).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1137%2FS003614450342480&link_type=DOI)[[Web of Science]](http://www.sciencemag.org/cgi/external_ref?access_num=000183800600002&link_type=ISI)
* 20. J. P. Eckmann, E. Moses, D. Sergi, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 14333 (2004).[[Abstract/Free Full Text]](http://www.sciencemag.org/cgi/ijlink?linkType=ABST&journalCode=pnas&resid=101/40/14333)
* 21. C. Cortes, D. Pregibon, C. Volinsky, *J. Comp. Graph. Stat.* **12**, 950 (2003).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1198%2F1061860032742&link_type=DOI)
* 22. P. Holme, C. R. Edling, F. Liljeros, *Soc. Networks* **26**, 155 (2004).
* 23. B. Wellman, C. Haythornthwaite, Eds., *The Internet in Everyday Life* (Blackwell, Oxford, 2003).
* 24. N. K. Baym, Y. B. Zhang, M. Lin, *New Media Soc.* **6**, 299 (2004).
* 25. Materials and methods are available as supporting material on Science Online.
* 26. H. Louch, *Soc. Networks* **22**, 45 (2000).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1016%2FS0378-8733%2800%2900015-0&link_type=DOI)[[Web of Science]](http://www.sciencemag.org/cgi/external_ref?access_num=000087144500003&link_type=ISI)
* 27. G. Kossinets, D. J. Watts, data not shown.
* 28. M. E. J. Newman, S. H. Strogatz, D. J. Watts, *Phys. Rev. E* **6402**, 026118 (2001).[[CrossRef]](http://www.sciencemag.org/cgi/external_ref?access_num=10.1103%2FPhysRevE.64.026118&link_type=DOI)
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**Supporting Online Material**

[**www.sciencemag.org/cgi/content/full/311/5757/88/DC1**](http://www.sciencemag.org/cgi/content/full/311/5757/88/DC1)

**Materials and Methods**

**References**

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**THIS ARTICLE HAS BEEN CITED BY OTHER ARTICLES:**

**The Spread of Behavior in an Online Social Network Experiment.**

D. Centola (2010)  
*Science***329**, 1194-1197   
   [**Abstract »**](http://www.sciencemag.org/cgi/content/abstract/329/5996/1194)    [**Full Text »**](http://www.sciencemag.org/cgi/content/full/329/5996/1194)    [**PDF »**](http://www.sciencemag.org/cgi/reprint/329/5996/1194)

**Social Network Structure of a Large Online Community for Smoking Cessation.**

N. K. Cobb, A. L. Graham, and D. B. Abrams (2010)  
*Am J Public Health***100**, 1282-1289   
   [**Abstract »**](http://ajph.aphapublications.org/cgi/content/abstract/100/7/1282)    [**Full Text »**](http://ajph.aphapublications.org/cgi/content/full/100/7/1282)    [**PDF »**](http://ajph.aphapublications.org/cgi/reprint/100/7/1282)

**Information dynamics shape the sexual networks of Internet-mediated prostitution.**

L. E. C. Rocha, F. Liljeros, and P. Holme (2010)  
*PNAS***107**, 5706-5711   
   [**Abstract »**](http://www.pnas.org/cgi/content/abstract/107/13/5706)    [**Full Text »**](http://www.pnas.org/cgi/content/full/107/13/5706/T1)    [**PDF »**](http://www.pnas.org/cgi/reprint/107/13/5706)

**From the Cover: Identifying the roles of race-based choice and chance in high school friendship network formation.**

S. Currarini, M. O. Jackson, and P. Pin (2010)  
*PNAS***107**, 4857-4861   
   [**Abstract »**](http://www.pnas.org/cgi/content/abstract/107/11/4857)    [**Full Text »**](http://www.pnas.org/cgi/content/full/107/11/4857/T04)    [**PDF »**](http://www.pnas.org/cgi/reprint/107/11/4857)

**Distinguishing influence-based contagion from homophily-driven diffusion in dynamic networks.**

S. Aral, L. Muchnik, and A. Sundararajan (2009)  
*PNAS***106**, 21544-21549   
   [**Abstract »**](http://www.pnas.org/cgi/content/abstract/106/51/21544)    [**Full Text »**](http://www.pnas.org/cgi/content/full/106/51/21544)    [**PDF »**](http://www.pnas.org/cgi/reprint/106/51/21544)

**From the Cover: Inferring friendship network structure by using mobile phone data.**

N. Eagle, A. Pentland, and D. Lazer (2009)  
*PNAS***106**, 15274-15278   
   [**Abstract »**](http://www.pnas.org/cgi/content/abstract/106/36/15274)    [**Full Text »**](http://www.pnas.org/cgi/content/full/106/36/15274)    [**PDF »**](http://www.pnas.org/cgi/reprint/106/36/15274)

**What is a social tie?.**

S. Wuchty (2009)  
*PNAS***106**, 15099-15100   
   [**Full Text »**](http://www.pnas.org/cgi/content/full/106/36/15099)    [**PDF »**](http://www.pnas.org/cgi/reprint/106/36/15099)

**Unlocking the Influence of Leadership Network Structures on Team Conflict and Viability.**

P. Balkundi, Z. Barsness, and J. H. Michael (2009)  
*Small Group Research***40**, 301-322   
   [**Abstract »**](http://sgr.sagepub.com/cgi/content/abstract/40/3/301)    [**PDF »**](http://sgr.sagepub.com/cgi/reprint/40/3/301)

**Spatial and Social Networks in Organizational Innovation.**

J. D. Wineman, F. W. Kabo, and G. F. Davis (2009)  
*Environment and Behavior***41**, 427-442   
   [**Abstract »**](http://eab.sagepub.com/cgi/content/abstract/41/3/427)    [**PDF »**](http://eab.sagepub.com/cgi/reprint/41/3/427)

**Representing the UK's cattle herd as static and dynamic networks.**

M. C Vernon and M. J Keeling (2009)  
*Proc R Soc B***276**, 469-476   
   [**Abstract »**](http://rspb.royalsocietypublishing.org/cgi/content/abstract/276/1656/469)    [**Full Text »**](http://rspb.royalsocietypublishing.org/cgi/content/full/276/1656/469)    [**PDF »**](http://rspb.royalsocietypublishing.org/cgi/reprint/276/1656/469)

**Dynamic spread of happiness in a large social network: longitudinal analysis over 20 years in the Framingham Heart Study.**

J. H Fowler and N. A Christakis (2008)  
*BMJ***337**, a2338   
   [**Abstract »**](http://www.bmj.com/cgi/content/abstract/337/dec04_2/a2338)    [**Full Text »**](http://www.bmj.com/cgi/content/full/337/dec04_2/a2338)    [**PDF »**](http://www.bmj.com/cgi/reprint/337/dec04_2/a2338)

**Factors Related to Willingness to Help Survivors of Intimate Partner Violence.**

M. L. Beeble, L. A. Post, D. Bybee, and C. M. Sullivan (2008)  
*J Interpers Violence***23**, 1713-1729   
   [**Abstract »**](http://jiv.sagepub.com/cgi/content/abstract/23/12/1713)    [**PDF »**](http://jiv.sagepub.com/cgi/reprint/23/12/1713)

**Culture and Education.**

M. L. Stevens (2008)  
*The ANNALS of the American Academy of Political and Social Science***619**, 97-113   
   [**Abstract »**](http://ann.sagepub.com/cgi/content/abstract/619/1/97)    [**PDF »**](http://ann.sagepub.com/cgi/reprint/619/1/97)

**Heterogeneity and Network Structure in the Dynamics of Diffusion: Comparing Agent-Based and Differential Equation Models.**

H. Rahmandad and J. Sterman (2008)  
*Management Science***54**, 998-1014   
   [**Abstract »**](http://mansci.journal.informs.org/cgi/content/abstract/54/5/998)    [**PDF »**](http://mansci.journal.informs.org/cgi/reprint/54/5/998)

**Relating Diarrheal Disease to Social Networks and the Geographic Configuration of Communities in Rural Ecuador.**

S. J. Bates, J. Trostle, W. T. Cevallos, A. Hubbard, and J. N. S. Eisenberg (2007)  
*Am. J. Epidemiol.***166**, 1088-1095   
   [**Abstract »**](http://aje.oxfordjournals.org/cgi/content/abstract/166/9/1088)    [**Full Text »**](http://aje.oxfordjournals.org/cgi/content/full/166/9/1088)    [**PDF »**](http://aje.oxfordjournals.org/cgi/reprint/166/9/1088)

**Predicting fate from early connectivity in a social network.**

D. B. McDonald (2007)  
*PNAS***104**, 10910-10914   
   [**Abstract »**](http://www.pnas.org/cgi/content/abstract/104/26/10910)    [**Full Text »**](http://www.pnas.org/cgi/content/full/104/26/10910)    [**PDF »**](http://www.pnas.org/cgi/reprint/104/26/10910)