Technological networks and the spread of computer viruses

Justin Balthrop, 1 Stephanie Forrest, 1,2* M. E. J. Newman, 3 and Matthew M. Williamson 4

1Dept. of Computer Science, University of New Mexico, Albuquerque, NM 87131, USA
2Santa Fe Institute, Santa Fe, NM 87505, USA
3Dept. of Physics and Center for the Study of Complex Systems, University of Michigan, Ann Arbor, MI 48109, USA
4HP Laboratories Bristol, Filton Road, Stoke Gifford, Bristol, BS34 8QZ, UK

*To whom correspondence should be addressed; E-mail: forrest@cs.unm.edu.

Computer infections such as viruses and worms spread over networks of contacts between computers, with different types of networks being exploited by different types of infections. Here we analyze the structures of several of these networks, exploring their implications for modes of spread and the control of infection. We argue that vaccination strategies that focus on a limited number of network nodes, whether targeted or randomly chosen, are in many cases unlikely to be effective. An alternative dynamic mechanism for the control of contagion, called throttling, is introduced and argued to be effective under a range of conditions.
Computer viruses and worms are an increasing problem for users of computers throughout the world. By some estimates 2003 was the worst year yet: viruses halted or hindered operations at numerous businesses and other organizations, disrupted ATMs, delayed airline flights, and even affected emergency call centers. The Sobig virus alone is said to have caused more than US$30 billion in damage.\(^1\) And most experts agree that the damage could easily have been much worse. For example, Staniford et al. describe a worm that could infect the entire Internet in around 30 seconds \([1]\). A worm of this scale and speed could launch a distributed denial-of-service attack that would bring the entire network to a halt, crippling critical infrastructure.

In this paper we use the term **virus** to refer to malicious software that requires help from computer users to spread to other computers. Email viruses, for instance, require someone to read an email message or open an attached file in order to spread. We use the term **worm** for infections that spread without user intervention. Because they spread unaided, worms can often spread much faster than viruses.

Computer infections such as viruses and worms spread over networks of contacts between computers, with different types of networks being exploited by different types of infections. The structure of contact networks affects the rate and extent of spreading of computer infections, just as it does for human diseases \([2, 3, 4, 5, 6]\), and understanding this structure is thus a key element in the control of infection.

Both traditional and network-based epidemiological models have been applied to computer contagion \([2, 3, 4]\). Recent work has emphasized the effects of a network’s **degree distribution**. A network consists of nodes or **vertices** connected by lines or **edges**, and the number of edges connected to a vertex is called its **degree**. Of particular interest are **scale-free networks**, in which the degree distribution follows a power-law, the fraction \(p_k\) of vertices with degree \(k\) falling off with increasing \(k\) as \(k^{-\alpha}\) for some constant \(\alpha\). This structure has been reported for

---

\(^1\)Citations documenting these events are listed on [http://www.cs.unm.edu/˜judd/virus.html](http://www.cs.unm.edu/˜judd/virus.html) as well as citations to each of the viruses and worms mentioned in this paper.
several technological networks including the Internet [7] and the world wide web [8, 9].

Infections spreading over scale-free networks are highly resilient to control strategies based on randomly vaccinating or otherwise disabling vertices. This is bad news for traditional computer virus prevention efforts, which use roughly this strategy. On the other hand, targeted vaccination, in which one immunizes the highest-degree vertices, can be very effective [10, 11].

It is important to appreciate that these results rely crucially on the assumption of a power-law degree distribution, and their derivation also assumes that the contact patterns between nodes are static. Many technological networks relevant to the spread of viruses, however, are not scale-free. Vaccination strategies focusing on highly connected network nodes are unlikely to be effective in such cases. Furthermore, network topology is not necessarily constant. In many cases the topology depends on the replication mechanism employed by a virus and can be manipulated by virus writers to circumvent particular control strategies that we attempt. If, for instance, targeted vaccination strategies were found to be effective against viruses spreading over scale-free networks, the viruses might well be rewritten so as to change the structure of the network to some non-scale-free form instead.

To make these ideas more concrete, we consider here four illustrative technological networks, each of which is vulnerable to attack: (A) the network of possible connections between computers using the Internet Protocol (IP); (B) a network of shared administrator accounts for desktop computers; (C) a network of email address books; (D) a network of email messages passed between users.

In network A, the IP network, each computer has a 32-bit IP address and there is a routing infrastructure that supports communication between any two addresses. We consider the network in which the nodes are IP addresses and two nodes are connected if communication is possible between the corresponding computers. Although some segments of the IP address space are invisible to others, the portion of the network within, for instance, a corporation will generally be
almost completely connected. Many epidemics spread over this IP network. Notable examples include the Nimda and SQLSlammer worms.

Network B is a product of the common operating system feature that allows computer system administrators to read and write data on the disks of networked machines. Some worms, including Nimda and Bugbear, can spread by copying themselves from disk to disk over this network.

Network C is a directed graph with nodes representing users and a connection from user $i$ to user $j$ if $j$'s email address appears in $i$’s address book. Many email viruses use address books to spread (e.g., ILOVEYOU). A closely related network is network D, which is an undirected graph in which the nodes represent computer users and two users are connected if they have recently exchanged email. Viruses such as Klez spread over this network.

Fig. 1 shows measured degree distributions for examples of each of the four networks. In network A all vertices have the same degree, so the distribution has a single peak at this value.
(blue histogram). In network B, the distribution consists of four discrete peaks, presumably corresponding to different classes of computers, administrators, or administration strategies (red histogram).

The two email networks have more continuous distributions and are shown as cumulative histograms. Although neither network has a power-law degree distribution, both have moderately long tails, which suggests that targeted vaccination strategies might be effective. Calculations show however that for the address-book network about 10% of the highest-degree nodes would need to be vaccinated to prevent an epidemic from spreading [6] while the email traffic network would require about 87%. The first of these figures is probably too high for an effective targeted vaccination strategy, and the second is clearly far too high. (Targeted vaccination would be entirely ineffective in the other two networks as well, because the nodes are much more highly connected.)

The two email networks illustrate the way in which different virus replication strategies can lead to different network topologies. An email virus could look for addresses in address books, thereby spreading over a network with a topology like that of network C, or it could look elsewhere on the machine, giving a topology more like D. Another example is provided by the Nimda virus, which infects web servers by targeting random IP addresses, producing a network like network A. However, if the virus had a more intelligent way of selecting IP addresses to attack (say, by inspecting hyperlinks), then it might spread over a topology more like that of the world wide web, which is believed to have a power-law degree distribution [8][9].

A control strategy is needed that is immune to changes in network topology and that does not require us to know the mechanisms of infections before an outbreak. Control strategies need to be highly effective against malicious infection but largely transparent to legitimate activities. A number of methods for containing computer epidemics have been proposed [12]. One such strategy is throttling, first introduced for the control of misbehaving programs [13] and recently
extended to computer network connections [14]. In this context, throttling limits the number of new connections a computer can make to other machines in a given time period. Because it works by limiting spreading rates rather than stopping spread altogether, the method does not completely eliminate infections but only slows them down. Frequently however this is all that is necessary to render a virus harmless or easily controlled by other means.

The network traffic generated by today’s viruses and worms is fundamentally different from normal network traffic. For a virus to spread it needs to propagate itself to many different machines, and to spread quickly it must do so at a high rate. For example, the Nimda worm attempts to infect web servers at a rate of around 400 new machines per second, which greatly exceeds the normal rate of connections to new web servers of about one per second or slower [15]. A throttling mechanism that limited connections to new web servers to about one per second would slow Nimda by a factor of 400 without affecting typical legitimate traffic. This could easily be enough to change a serious infection into a minor annoyance, which could then be eliminated by traditional means. Slowing the spread of Nimba by a factor of 400 (from a day to over a year) would have allowed plenty of time to develop and deploy signatures and prophylactic software patches. (Of course, if throttling were implemented on only a subset of the nodes in a network, then infections could spread more easily.) In addition to reducing virus spread, throttling has the practical benefit of reducing the amount of traffic generated by an epidemic, thus reducing demand on networking equipment—often the primary symptom of an attack.

To summarize, approaches for controlling epidemics in computer networks are unlikely to be generally effective if they rely on detailed assumptions about network topology. Moreover, the topology of contact networks is often dependent on a virus’s replication and infection strategy. Better and more general approaches to restricting contagion are needed. Throttling provides one example of how rapidly spreading infections may be controlled in the future. Throttling can be effective for all network topologies, although only if normal network traffic...
is significantly different from that generated by spreading epidemics. Throttling does not eliminate computer epidemics; it simply causes them to spread more slowly, allowing time for the slower mechanisms of conventional prevention and clean-up.

The disparity between the speed of computer attacks (machine and network speed) and the speed of manual response (human speed) has increased in recent years. As this trend continues, automated mechanisms like throttling will likely become an essential tool for controlling those attacks, complementing the largely manual approach of software patching in use today. The idea of rate limits is not specific to viruses, and could be applied to any situation in which an attack or cascading failure occurs faster than possible human response.

The authors gratefully acknowledge Jeff Gassaway for help collecting the email address book data set, Chaz Hickman for the administrator data set, and Joshua Tyler and Bernardo Huberman for the email traffic data set. This work was funded in part by the James S. McDonnell Foundation, the National Science Foundation, the Defense Advanced Projects Research Agency, Intel Corp., and the Santa Fe Institute.

References and Notes

[1] S. Staniford, V. Paxson, and N. Weaver, How to own the internet in your spare time. In Proceedings of the USENIX Security Symposium (2002).

[2] J. O. Kephart and S. R. White, Directed-graph epidemiological models of computer viruses. In Proceedings of the 1991 IEEE Computer Society Symposium on Research in Security and Privacy, pp. 343–359, IEEE Computer Society, Los Alamitos, CA (1991).

[3] R. Pastor-Satorras and A. Vespignani, Epidemic spreading in scale-free networks. Phys. Rev. Lett. 86, 3200–3203 (2001).
[4] A. L. Lloyd and R. M. May, How viruses spread among computers and people. *Science* **292**, 1316–1317 (2001).

[5] H. Ebel, L.-I. Mielsch, and S. Bornholdt, Scale-free topology of e-mail networks. *Phys. Rev. E* **66**, 035103 (2002).

[6] M. E. J. Newman, S. Forrest, and J. Balthrop, Email networks and the spread of computer viruses. *Phys. Rev. E* **66**, 035101 (2002).

[7] M. Faloutsos, P. Faloutsos, and C. Faloutsos, On power-law relationships of the internet topology. *Computer Communications Review* **29**, 251–262 (1999).

[8] R. Albert, H. Jeong, and A.-L. Barabási, Diameter of the world-wide web. *Nature* **401**, 130–131 (1999).

[9] J. M. Kleinberg, S. R. Kumar, P. Raghavan, S. Rajagopalan, and A. Tomkins, The Web as a graph: Measurements, models and methods. In *Proceedings of the International Conference on Combinatorics and Computing*, number 1627 in Lecture Notes in Computer Science, pp. 1–18, Springer, Berlin (1999).

[10] R. Albert, H. Jeong, and A.-L. Barabási, Attack and error tolerance of complex networks. *Nature* **406**, 378–382 (2000).

[11] D. S. Callaway, M. E. J. Newman, S. H. Strogatz, and D. J. Watts, Network robustness and fragility: Percolation on random graphs. *Phys. Rev. Lett.* **85**, 5468–5471 (2000).

[12] D. Moore, C. Shannon, G. Voelker, and S. Savage, Internet quarantine: Requirements for containing self-propagating code. In *Proc. 22nd Ann. Joint Conf. of IEEE Computer and Communication Societies (INFOCOM)* (2003).
[13] A. Somayaji and S. Forrest, Automated response using system-call delays. In *Proceedings of the 9th USENIX Security Symposium*, pp. 185–197, Denver, CO (2000).

[14] M. M. Williamson, Resilient infrastructure for network security. *Complexity* (in press). Available from [http://www.hpl.hp.com/techreports/2002/HPL-2002-273.html](http://www.hpl.hp.com/techreports/2002/HPL-2002-273.html)

[15] M. M. Williamson, Throttling viruses: Restricting propagation to defeat malicious mobile code. In *Proceedings of ACSAC Security Conference*, pp. 61–68, Las Vegas, Nevada (2002). Available from [http://www.hpl.hp.com/techreports/2002/HPL-2002-172.html](http://www.hpl.hp.com/techreports/2002/HPL-2002-172.html)