

# Evolution of a modular software network

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**"Evolution behaves like a tinkerer" (François Jacob, *Science*, 1977). Software systems provide a singular opportunity to understand biological processes using concepts from network theory. The Debian GNU/Linux operating system allows us to explore the evolution of a complex network in a unique way. The modular design detected during its growth is based on the reuse of existing code in order to minimize costs during programming. The increase of modularity experienced by the system over time has not counterbalanced the increase in incompatibilities between software packages within modules. This negative effect is far from being a failure of design. A random process of package installation shows that the higher the modularity, the larger the fraction of packages working properly in a local computer. The decrease in the relative number of conflicts between packages from different modules avoids a failure in the functionality of one package spreading throughout the entire system. Some potential analogies with the evolutionary and ecological processes determining the structure of ecological networks of interacting species are discussed.**

network evolution | evolvability | robustness | community assembly | food webs

Complex systems represented by networks pervade all sciences (1). Since the publication, 10 yr ago, of studies focused on the topological characterization and dynamical implications of networks of very different nature (2–8), little progress has been made on understanding the evolution of such complex systems (see, however, refs. 9–11). Most studies assume that the architecture of these networks is static. However, on the World-Wide Web, pages and links are created and lost every minute (12). The structure of the current power grid depends on how it has grown over the years (13), and food webs are shaped continually through community assembly processes (14). Unraveling how these complex networks grow and change through time is a crucial task for understanding their long-term dynamics.

Software systems, as computer operating systems, are under the constraints of hardware architecture and user requirements (15). Functionality is the main goal of software design. Developers need to make the system capable of accomplishing new tasks without excessive cost, so that modifying or adding a single feature does not require the update of preexisting code throughout the system. This ability to reuse existing code allows the system to build up in a modular and hierarchical fashion (16). The distributed and collaborative nature of software design, in which many individuals work only on small pieces of the whole system, requires developing a strategy to support software growth without losing functionality. Indeed, this attributed modular approach can enhance functionality (17, 18).

Such design is expected to improve evolvability by limiting the interference between different functions. These interferences are a consequence of the software development process itself and may reduce the functional diversification of the operating system. For example, incompatibilities among functionally similar libraries required by different groups of programs may impede the correct installation of a complete set of software packages. Therefore, there is a trade-off between reusing many pieces of existing code and the emergence of incompatibilities among software packages.

The Debian GNU/Linux operating system offers a unique opportunity to study the evolution of this trade-off over time, due to its package interaction system and its release schedule (see Fig. 1). In Debian, most software packages reuse code of others in order to work properly (i.e., dependencies; package *i* needs package *j* for being functional) or have incompatibilities with other packages that impede the former to be installed in the same local computer (i.e., conflicts; package *i* prevents package *j* from being installed; see *Materials and Methods*).

In this paper, we first characterize the evolving modular structure of the network of dependencies between software packages for the first 10 releases of the Debian GNU/Linux operating system. Second, we explore the role of conflicts between packages in determining the functionality of the system by using a package installation process in a local computer. Last, we discuss potential parallels between the architecture and dynamics of software networks and that of ecological webs of interacting species.

## Results

We have compiled the binary i386 packages, including their dependencies and conflicts, of the first major stable versions of the Debian/GNU operating system released since the project began in 1993 (see *Materials and Methods* and *SI Appendix*). The growth of the Debian/GNU Linux operating system from one release to the subsequent is summarized in three steps: some packages are deprecated, others are kept between versions, and new ones are added (see Fig. 2). The number of packages that are deprecated between releases and those that persisted increased exponentially over time ( $F_{1,7} = 693.5$ ,  $p < 0.001$ , and  $F_{1,7} = 165.2$ ,  $p < 0.001$ , respectively; see *Materials and Methods*). The number of new packages added in the most recent version was slightly smaller than in the previous one. If we discard it from the analysis, the number of new packages also increased exponentially over time ( $F_{1,6} = 216.9$ ,  $p < 0.001$ ). The total number of packages, dependencies, and conflicts increased exponentially with each version, ranging from 448 to 28,245 ( $F_{1,8} = 1,117.8$ ,  $p < 0.001$ ), from 539 to 101,521 ( $F_{1,8} = 603.1$ ,  $p < 0.001$ ), and from 28 to 4,755 ( $F_{1,8} = 307.1$ ,  $p < 0.001$ ), respectively (see *SI Appendix, Table S1*). Data from the most recent release seem to indicate the beginning of an asymptotic stationary behavior for the growth of both packages and interactions (their exclusion from the regression analysis increased the fit to  $F_{1,7} = 1,064.6$ ,  $p < 0.001$ , and to  $F_{1,7} = 466.8$ ,  $p < 0.001$ , for dependencies and conflicts, respectively). Neither the ratio between the number of dependencies and the number of conflicts, nor the fraction of packages without any interactions showed a linear tendency over time ( $F_{1,8} = 1.5$ ,  $p = 0.263$ ,  $21.2 \pm 5.18$  mean and standard deviation; and  $F_{1,8} = 0.078$ ,  $p = 0.787$ ,  $0.132 \pm 0.054$  mean and standard deviation, respectively).

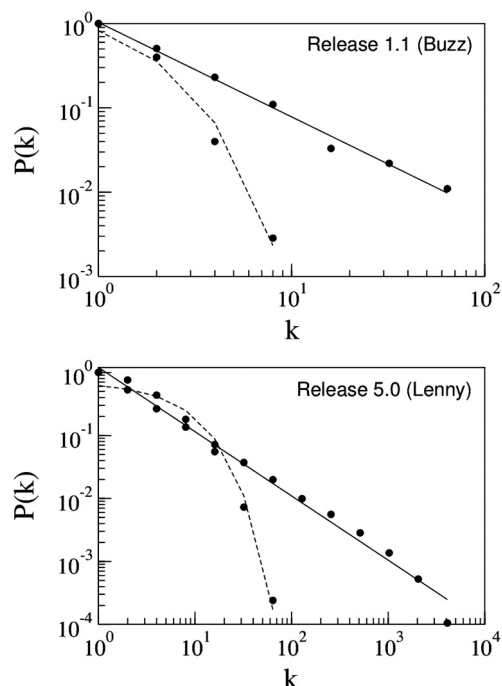
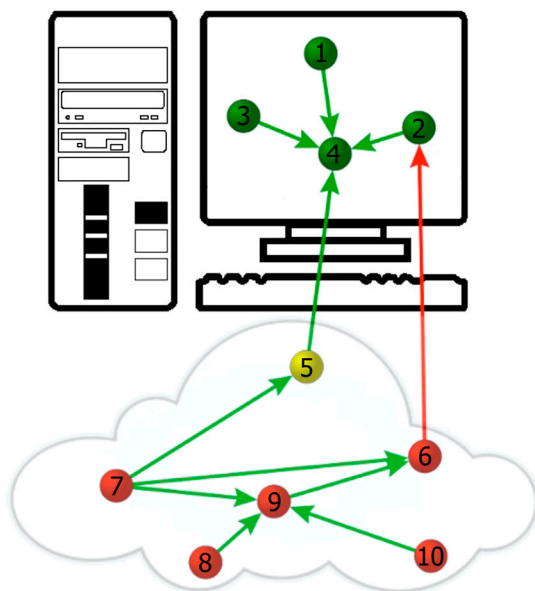
The cumulative degree distribution for the outgoing dependencies (number of packages necessary for *i* to work) fit an

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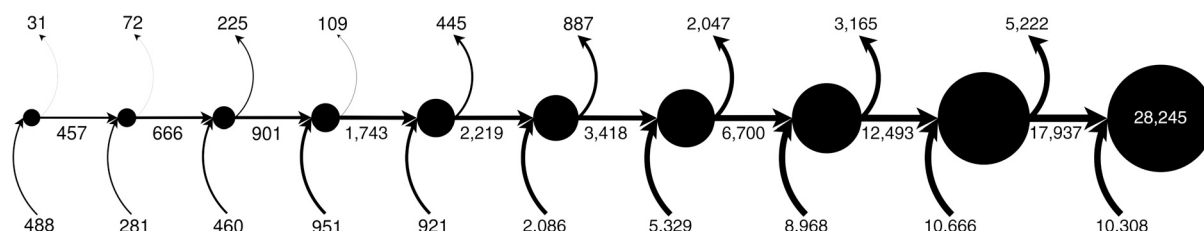
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**Fig. 3.** Cumulative degree distribution of the number of incoming (solid lines) and outgoing (dashed lines) dependencies for the software packages of the first and last releases (on top and on bottom, respectively) of the Debian GNU/Linux operating system analyzed here. The figures depict the probability,  $P(k)$ , for a package to depend on or to be needed by at least  $1, 2, 3, \dots, k$  packages to work. Both axes are in logarithmic scale. In all cases, the best fit for the outgoing dependencies is an exponential function, whereas for the incoming dependencies is a power law (see also [SI Appendix, Fig. S1](#)).

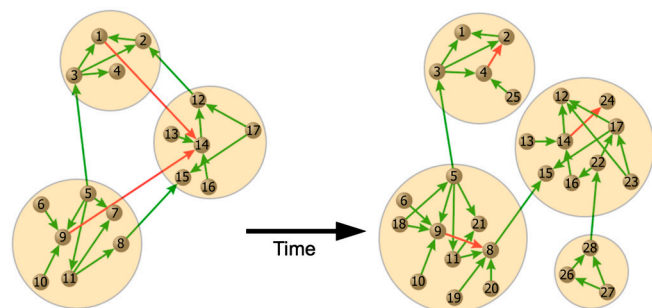
only by a few packages (see also *SI Appendix, Fig. S1*). In other words, the network of dependencies showed a scale-free distribution for the incoming dependencies over time, indicating that the new packages added on successive releases depended mainly on the most connected ones (i.e., those packages used by many others).



mained constant through time ( $6.7 \pm 0.67$ , mean and standard deviation, respectively;  $F_{1,8} = 1.5$ ,  $p = 0.250$ ; see *SI Appendix, Fig. S2*). Therefore, the new modules originated in subsequent releases contained few packages, indicating that the bulk of new packages added over time joined to the few large modules created in the earliest versions (see Fig. 4 and *SI Appendix, Fig. S3*).

Yet, the fraction of conflicts within modules increased linearly over time (ranging from 0.50 to 0.74;  $F_{1,8} = 30.45$ ,  $p < 0.001$ ) while the fraction of dependencies within modules remained constant ( $0.677 \pm 0.031$ , mean and standard deviation, respectively;  $F_{1,8} = 0.05$ ,  $p = 0.831$ ; see Fig. 4 and *SI Appendix, Fig. S4*). Therefore, the increase in the modularity of the dependencies has not avoided the conflicts within modules during the exponential growth of the operating system. This fact means that, as the modular structure of the network of dependencies increased (up to the sixth release), the fraction of conflicts between modules decreased (Fig. 4). Since then, although the modular structure has not grown significantly, the fraction of conflicts between modules has continued decreasing.

The dynamical implications of this result are shown by a random process of package installation in a local computer (see Fig. 1 and *Materials and Methods*). The fraction of packages that can be installed by a random process decreased linearly through time (ranging from 0.957 to 0.711;  $F_{1,8} = 40.1$ ,  $p < 0.001$ ). A priori, we might think that the higher the modularity of the network, the lower the functionality of the operating system, measured as number of packages installed from the pool of available software. However, other factors, such as the number of conflicts between packages (which also increased over time) may be responsible for the reduction in the fraction of software installed. To rule this effect out, we performed a random process of package installation in which the modular structure of the network of dependencies is deliberately broken by a local rewiring algorithm (see *Materials and Methods*). Hence, we can estimate the effect of the modular structure on the installation process. In almost all versions, the modularity of the network of dependencies increased significantly the fraction of packages installed in a local computer compared with what is expected from the randomization ( $p < 0.01$ , except for releases 2.0 and 3.0,  $p = 0.14$  and



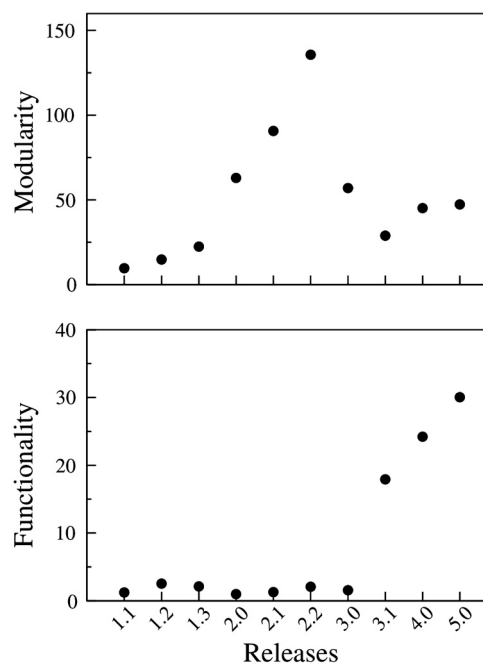
**Fig. 4.** Evolution of the modular structure of the network of dependencies between packages of the Debian GNU/Linux operating system. Packages are represented by nodes. A green arrow from package  $i$  to package  $j$  indicates that package  $i$  depends on package  $j$ , and a red arrow indicates that package  $i$  has a conflict with package  $j$ . Packages within a module (depicted by a big circle) have many dependencies between themselves and only a few with packages from other modules. During the growth of the operating system, the modular structure of the network of dependencies has increased: (i) The new packages added in successive releases depended mainly on previously existing packages within the same module, and hence, the size of the modules created in earlier releases increased over time; (ii) the number of modules also increased, although the new modules consisted only of a few new packages; and (iii) the relative number of dependencies between packages from different modules decreased. Moreover, the relative number of conflicts between packages from different modules decreased, whereas those within modules increased through the different releases of the operating system.

$p = 0.10$ , respectively). The  $Z$  score calculated to compare this effect across releases (see *Materials and Methods*) did not show a significant linear increase over time until release 3.0 ( $1.685 \pm 0.569$ , mean and standard deviation, respectively;  $F_{1,5} = 0.059$ ,  $p = 0.818$ ). Since then, the  $Z$  score increased notably (ranging from 17.9 to 30.1; see Fig. 5).

In summary, from release 1.1 to release 2.2, the significant exponential increase of the modularity of the network of dependencies (measured by the  $Z$  score) did not cause a significant positive effect on the fraction of software packages installed. However, from release 3.1 to the last release analyzed (5.0), the lower and nonincreasing modularity was responsible for a positive strong effect on the fraction of software installed in a local computer (Fig. 5). Debian 3.1, released in 2005, proved to be a break point between these two opposite tendencies. Although versions 3.0 and 3.1 increased the amount of software to practically double the size of the previous release, Debian 3.1 updated 73% of the packages found in Debian 3.0. These and other important changes are mainly the result of the long time elapsed since the previous version was released (almost 3 y, the longest interval between releases in the history of Debian).

## Discussion

The increase of the modular structure of the operating system over time detected in this paper seems to be an effective strategy for allowing the growth of software, minimizing the risk of collapse due to failures in the functionality of some packages. This strategy has also been reported for the ecological and evolutionary processes structuring food webs (19). The failure in the functionality of a software package, or the extinction of a species in an ecological community, would not propagate its negative effects to packages (species) from other modules, minimizing the risk of a collapse of the entire system. Therefore, understanding the evolution of a computer operating system can shed light



**Fig. 5.** Changes of the modular structure (measured as the  $Z$  score of the modularity compared to a randomization of the modular structure) and functionality (measured as the  $Z$  score of the fraction of packages installed in a local computer compared to that installed from a randomization of the modular structure) for the network of dependencies of the releases of Debian GNU/Linux operating system analyzed here. The positive effects of the modular structure on the functionality shows up strongly in the last three releases (linear increase), although the exponential increase of the modularity happens in the first ones.



on the evolutionary and ecological constraints shaping communities of interacting species. For example, we can investigate how species richness increases without jeopardizing the coexistence of the entire community. Minimizing the risks of competitive exclusion between species playing the same role in a community is equivalent to reducing software incompatibilities between modules of dependencies to increase functionally. The spatial segregation in the distribution of species represents an effective modular process analogous to the compartmentalization of the software network: It allows a higher regional species richness (software packages pool) at the expense of reducing local diversity minimizing competitive exclusion.

The Debian GNU/Linux operating system provides a unique opportunity to make this and other analogies within the evolutionary and ecological framework, determining the structure of ecological networks of interacting species. Both processes occur at different timescales. On the evolutionary timescale, speciation and extinction (i.e., macroevolution) can be translated into the creation of new packages and the deprecation of those rendered obsolete from one version to the next. On the ecological timescale, colonization and local extinction (i.e., community assembly) would be equivalent to the package installation process in a local computer. Dependencies and conflicts between packages mimic predator–prey interactions and competitive exclusion relationships, respectively. Because of these relations, only a subset of the available packages can be installed in a computer because only a subset of the species pool can coexist in a local ecological community. Moreover, there is an interplay between macroevolution and community assembly, because the interactions introduced by the new species (packages) alter the dynamics of the colonization/extinction (installation) in a local community (computer).

## Conclusions

During the exponential growth of the Debian GNU/Linux operating system, the reuse of existing code showed a scale-free distribution for the incoming dependencies and an exponential one for the outgoing dependencies. The modularity of the network of dependencies between packages as well and the number of structural modules increased over time. However, this increase in modularity did not avoid the increase in software incompatibilities within modules. Far from being a failure of software design, the modular structure of the network allows a larger fraction of the pool of available software to work properly in a local computer when the installation follows a random process. Decreasing conflicts between modules impedes the exclusion of entire modules of packages from the installation process. This positive effect of the modular structure was much larger in the last three releases, although the increase in modularity was not as high as it was for the first ones.

Further research on network evolution and local assembly dynamics in this and in other engineer systems will open an opportunity window for biologists and computer scientists to collaborate and address fundamental problems in biology. Let us keep in mind the words of Uri Alon (20): “The similarity between the creations of a tinkerer and engineer also raises a fundamental scientific challenge: understanding the laws of nature that unite evolved and designed systems.”

## Materials and Methods

**Dataset.** In the Debian GNU/Linux operating system, most software packages depend on or have conflicts with other packages in order to be installed on a local computer. By “dependencies” (package  $i$  depends on package  $j$ ), we mean that package  $j$  has to be installed first on the computer for  $i$  to work. By “conflicts” (package  $i$  has a conflict with package  $j$ ), we mean that package  $i$  cannot be installed if  $j$  is already on the computer. However, this fact does not necessarily mean that package  $j$  also has a conflict with package  $i$ : Sometimes package  $j$  is an improved version of package  $i$  in a way that if  $i$

is already installed in the system, then  $j$  improves it, but if  $j$  is installed then it already contains  $i$  and the latter cannot be installed. We have compiled the list of software packages, along with the network of dependencies and conflicts, of the 10 major versions released since 1996. The list of packages and interactions can be downloaded from the Web site of this journal (see [SI Appendix](#) for more details).

**Statistical Analysis.** We have performed exponential regressions to quantify the increase in the number of packages that were deprecated, the new ones that were added, and those that persisted among the 10 releases analyzed. We also characterized the increase in the number of dependencies and conflicts through releases using exponential regressions. The change of the ratio between the number of dependencies and the number of conflicts through releases was tested using a linear regression. The fits of the cumulative degree distributions for dependencies and conflicts that are shown are those with the highest  $F$ -test statistic between the two applied functions (exponential and power law) using multiplicative bins (see [SI Appendix, Fig. S1](#)). The increase of the fraction of dependencies and conflicts within modules through releases was tested using linear regressions. We used linear and exponential regressions to test the change in the  $Z$  score (obtained for allowing the comparison of the modularity across networks) through releases. Linear regressions were also used to characterize the relationship between the number of modules and the number of packages with dependencies through releases. Finally, the decrease in the number of packages installed by a random process through releases and its relationship with the  $Z$  score of the modularity were tested using linear regressions.

**Modularity Analysis.** We have used a heuristic method, based on modularity optimization (21), to extract the modular structure of the network of dependencies of software packages constituting the different releases of the Debian GNU/Linux operating system. The “Louvain” method (22) is a greedy algorithm implemented in C++ that allows one to study very large networks. The excellent results in terms of modularity optimization, given by the well-known “Netcarto” software based on simulated annealing (23, 24), is limited when dealing with large networks, where extracting modularity optimization is a computationally hard problem. It has been shown that the Louvain method outperforms Netcarto in terms of computation time (22). In addition, the Louvain method is able to reveal the potential hierarchical structure of the network, thereby giving access to different resolutions of community detection (25). The statistical significance of the modularity was calculated by performing, for each release, 1,000 randomizations of the network of dependencies, keeping exactly the same number of dependencies per package, but reshuffling them randomly using a local rewiring algorithm (26). The  $p$  value was calculated as the fraction of random networks with a modularity value equal to or higher than the value obtained for the compiled network. In order to rule out the differences (in terms of connectance, number of packages, etc.) in the comparison of the modularity across networks, we calculated a  $Z$  score defined as the modularity of the compiled network of dependencies minus the mean modularity of the randomizations, divided by the standard deviation of the randomizations.

**Local Installation Process.** The aim of the local installation process is to calculate the distribution of the maximum number of packages that can be correctly installed in a computer by a random process of software installation. We have performed 1,000 replicates of the local installation process for each release of the Debian/GNU Linux operating system, ensuring that the asymptotic behavior of the variance was reached. Only packages with interactions (dependencies and/or conflicts) have been used in the process, and no subset of basic packages has previously been installed (both conditions differ from the algorithm applied by Fortuna and Melián, ref. 27). The algorithm randomly selects a package and checks whether it, or the packages it depends on, have a conflict with those that have already been installed. If the package has a conflict with an already installed one, it is discarded. If it has no conflict with installed packages, the algorithm checks whether any of the packages it depends on directly or indirectly (by successive dependencies) has been discarded or has a conflict with an already installed package. In that case, it is discarded too. Otherwise, it is installed with all the packages it depends on, directly as well as indirectly. The process continues until no more packages are available to be installed. In the few cases where a package depends on two packages having a reciprocal conflict (because one or the other is needed for the installation of the selected package), we choose randomly one of them and discard the other. The randomization of the network of dependencies used for testing the effect of the modularity on the local installation process was the same describe above (*Modularity Analysis*).



The number of conflicts between packages and the identity of who has a conflict with whom have remained unchanged, as in the compiled networks. We performed 1,000 replicates of the installation process for each randomization, and generated 100 random networks of dependencies for each release. The fraction of random networks in which the fraction of packages installed was equal to or higher than the value obtained for the modular network was used as the  $p$  value. A  $Z$  score was calculated for comparing, across releases, the fraction of packages installed using the modular networks with that of randomizations. The  $Z$  score was defined as the mean fraction of packages installed using the modular network minus the

mean fraction of packages installed using the randomizations, divided by the standard deviation of the randomizations.

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## SUPPLEMENTARY INFORMATION

The Debian project was born in 1993. Since then, eleven stable versions have been released to date, all of them named after a character in the movie Toy Story (Buzz (1996), Rex (1996), Bo (1997), Hamm (1998), Slink (1999), Potato (2000), Woody (2002), Sarge (2005), Etch (2007), Lenny (2009), and Squeeze (2011)). In this study we have compiled the binary i386 packages, along with their dependencies and conflicts of the first ten releases (from Buzz to Lenny). They were downloaded from <http://archive.debian.org/debian/dists/>. The files (in txt format) are available from the website of this journal as a zip folder.

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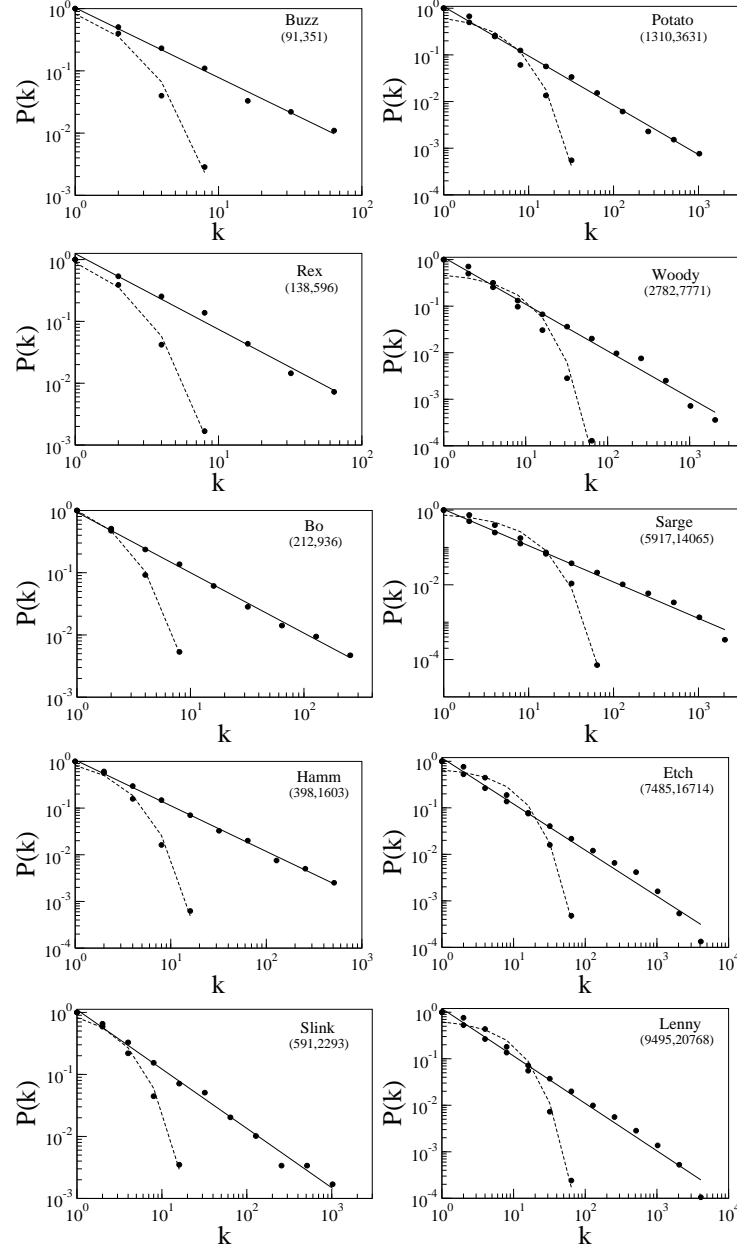
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Table I.  
Description of the components of the interaction network of Debian GNU/Linux over time

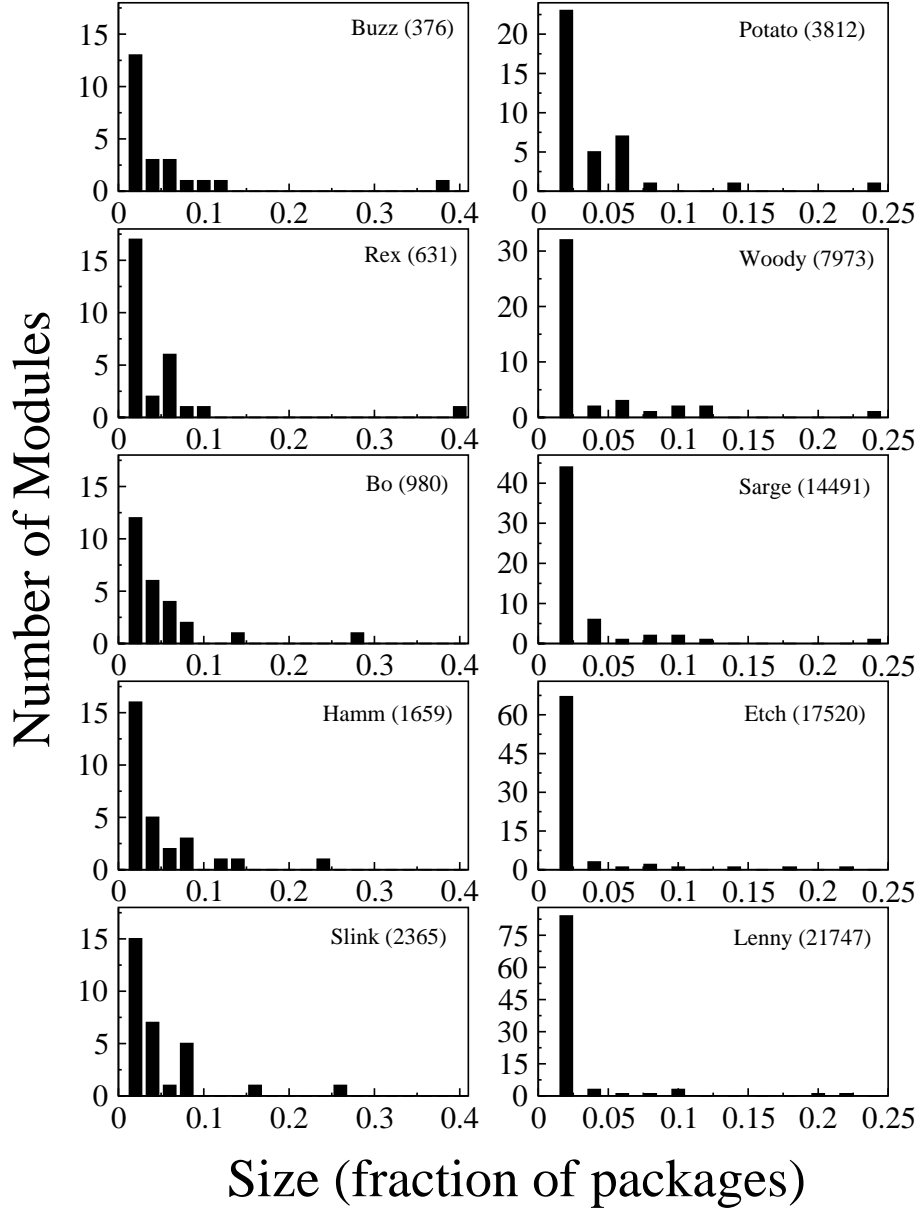
(release, release name, release date, number of packages, number of packages with interactions, number of dependencies, number of conflicts, number of packages with outgoing dependencies, number of packages with outgoing conflicts, number of packages with incoming dependencies, and number of packages with incoming conflicts)

Release	Codename	Year	Packages	Inter_Pack	Dependencies	Conflicts	Pack_ $K_{out}^{dep}$	Pack_ $K_{out}^{con}$	Pack_ $K_{in}^{dep}$	Pack_ $K_{in}^{con}$
1.1	Buzz	1996	488	379	539	28	351	27	91	22
1.2	Rex	1996	738	633	943	29	596	26	138	23
1.3	Bo	1997	1126	984	1744	62	936	56	212	53
2.0	Hamm	1998	1852	1677	3631	199	1603	166	398	140
2.1	Slink	1999	2664	2395	5983	336	2293	257	591	237
2.2	Potato	2000	4305	3851	10617	632	3631	456	1310	413
3.0	Woody	2002	8747	8040	28225	1687	7771	1100	2782	1062
3.1	Sarge	2005	15658	14657	66125	3148	14065	2034	5917	1783
4.0	Etch	2007	23159	18632	90213	4530	16714	2763	7485	2946
5.0	Lenny	2009	28245	22919	101521	4755	20768	3011	9495	3273

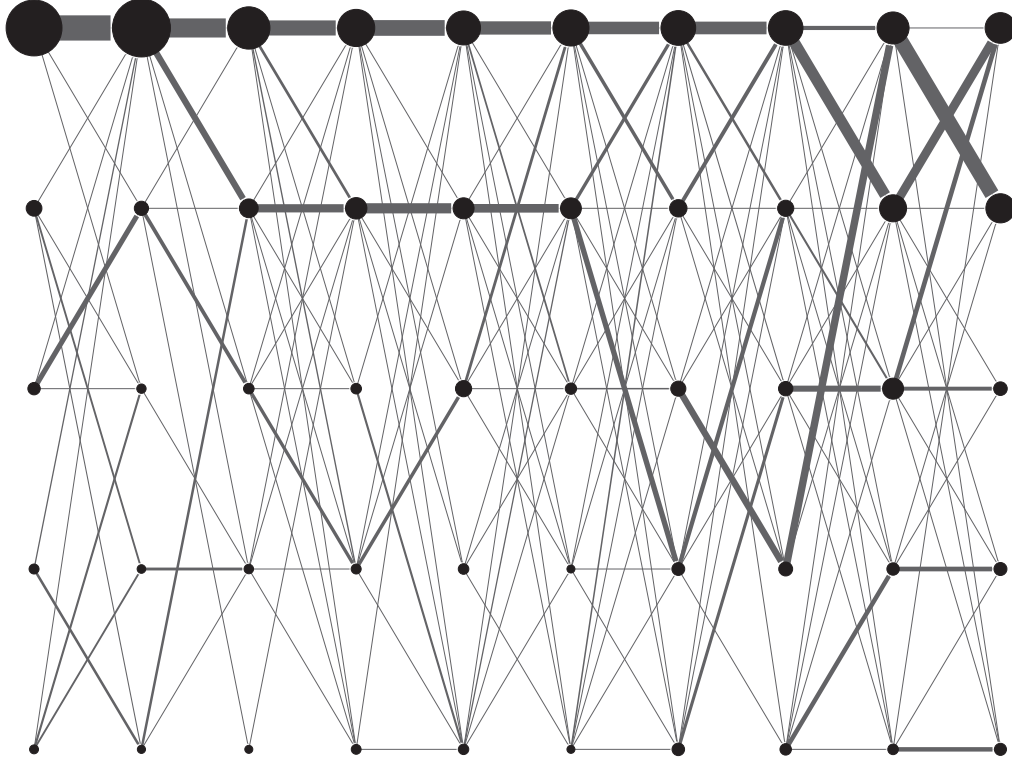




**Figure 1:** Cumulative degree distribution of the number of incoming (solid lines) and outgoing (dashed lines) dependencies for the software packages of the first ten releases of the Debian GNU/Linux operating system (from top to bottom and from left to right). The figures depict the probability,  $P(k)$ , for a package to depend on or to be needed by at least, 1, 2, 3, ...,  $k$  packages to work. Both axes are in logarithmic scale. In every release the best fit for the outgoing dependencies is an exponential function while for the incoming dependencies is a power-law. Inset, the number of packages with incoming or outgoing dependencies (in parenthesis, respectively) and the name of the release are indicated.

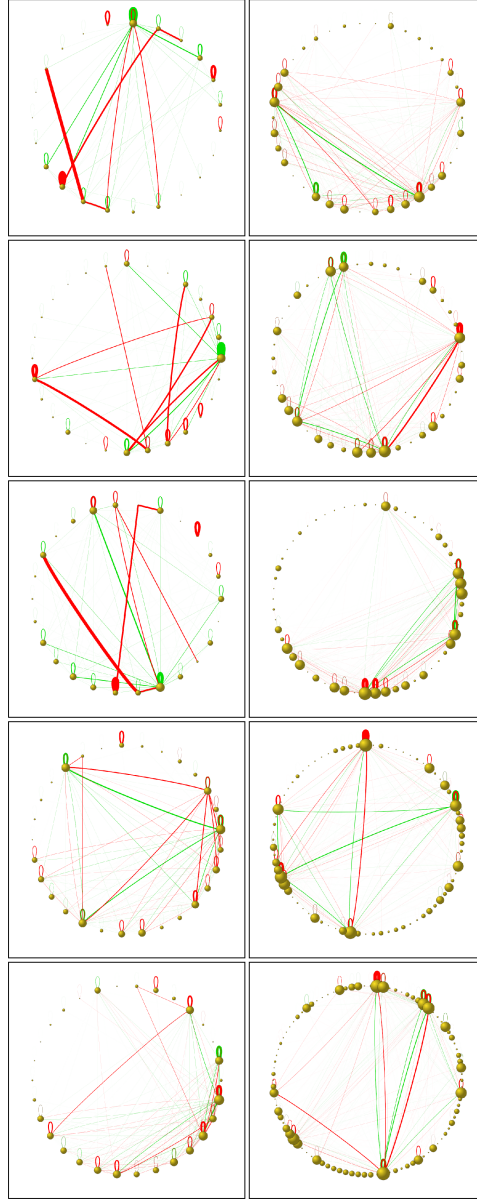


**Figure 2:** *Distribution of the size of the modules identified by the modularity algorithm for each release of the Debian GNU/Linux operating system (release name and total number of interacting packages inside each plot). The first five releases (on the left) consist of approximately the same number of modules (between 23 and 30). In the successive releases (on the right) the number of modules increased over time (until 94 for the most recent version). However, the size of most modules was smaller over time in relation to the total number of interdependent packages constituting each release. The number of modules consisting of at least 5% of the total number of interdependent packages oscillated between 6 and 8 for all releases.*



**Figure 3:** *Schematic representation of the fate of the modules of interdependent packages along the first ten releases of the Debian GNU/Linux operating system. Nodes along each column represent the five largest modules of each release, and their size is proportional to the number of packages constituting each release. The thickness of the line between two nodes indicates the fraction of packages from one module in one release that are assigned to another module in the next release (from left to right). Most nodes only have one thick line in each direction, meaning that the packages constituting the largest modules do not tend to break up themselves in several modules in the next release, but to keep together as one component of the new module.*

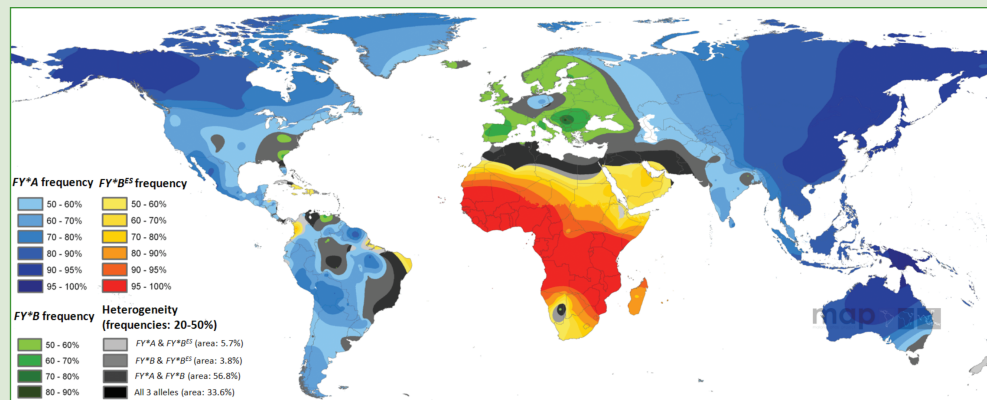




**Figure 4:** *Evolution of the modularity in a software network. The modular structure of the first ten releases of the Debian GNU/Linux operating system are represented (from top to bottom and from left to right). Nodes in each plot depict modules and links indicate the fraction of dependencies (in green) and conflicts (in red) between packages assigned to different modules (or within modules, loops). The size of the nodes is proportional to the logarithm of the number of packages. The number of modules and the fraction of conflicts within modules increased over time while the fraction of dependencies within modules remained constant. (Note that red color can hide green color in the loops).*

## Red blood cell receptor affects vivax malaria susceptibility

*Plasmodium vivax*, a major cause of human malaria, invades red blood cells primarily by binding to a cell surface receptor known as Duffy blood-group antigen (Fy). Christopher King et al. (pp. 20113–20118) found that binding to Fy by a parasite invasion protein known as *P. vivax* Duffy binding protein (PvDBP) decreased by 41–50% in red blood cells that expressed Fy<sup>a</sup>, an allele that is distinguished from Fy<sup>b</sup> by a single point mutation. The authors found that antibodies to PvDBP were better able to block binding of the PvDBP to the surfaces of Fy<sup>a</sup> cells compared with Fy<sup>b</sup> cells. Upon examining clinical *P. vivax* infections in an endemic region of the Brazilian Amazon, the authors found that the Fy<sup>a</sup> allele, which dominates in many Asian and American populations where vivax malaria is most highly endemic, was associated with a decreased susceptibility to vivax malaria, while increased susceptibility to vivax malaria was associated with increased expression of Fy<sup>b</sup>. The findings indicate that Fy<sup>a</sup> may have been positively selected to improve human fitness to vivax malaria, and that the efficacy of a PvDBP-based vaccine may differ among populations with different Fy phenotypes, according to the authors. — S.R.

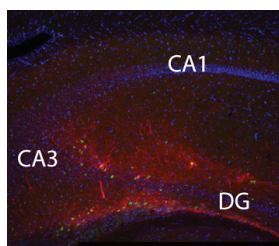


Global frequencies of the Fy alleles.

## Stem cell-derived neurons functionally integrate in living mice

Neurons derived from stem cells hold great promise for the treatment of neurological diseases, but therapeutic success hinges on the ability of transplanted neurons to integrate into existing circuitry in vivo. Previous studies suggest that, after transplantation into living animals, human stem cell-derived neurons can receive neuronal signals and ameliorate signs of neurodegeneration. But whether the human cells completely integrate with—and regulate—established neuronal networks in other animals remains unclear. Jason Weick et al. (pp. 20189–20194) investigated the ability

of transplanted neurons to integrate in vitro and in the mouse brain using transgenic human embryonic stem cell (hESC)-derived neurons engineered to be specifically activated by light. The authors grew the cells in culture with mouse neurons that displayed a synchronized network activity known



Transplanted hESC-derived neurons (green) integrate with host neurons (red) in the mouse brain.

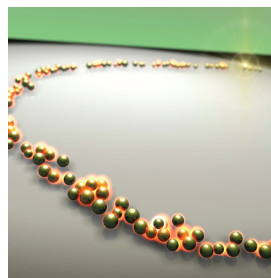
as “bursting”, and found that the hESC-derived neurons progressively developed bursting behavior by functionally integrating with the mouse cell network. Furthermore, human neurons triggered bursting behavior in the mouse cell network upon stimulation with light. Light stimulation also elicited responses in existing mouse neurons from the brain slices of mice transplanted with hESC-derived neurons. These findings suggested to

the authors that transplanted human neurons can participate in and modulate neural network activity in other animals through functional integration. According to the authors, the findings may prove useful for the treatment of Parkinson and Alzheimer’s diseases, stroke, and epilepsy. — N.Z.

## Electric fields at the surface of tiny particles

Surface plasmons are electron oscillations at the surface of a material that create large local electric fields. Researchers recently found that surface plasmons in tiny metal particles can couple together and move in step, amplifying the electric field, but resistance from the metal can dampen the oscillations. Wei-Shun Chang et al. (pp. 19879–19884) expanded on theoretical studies of coupled surface plasmons in metal particles by explor-

ing whether the electromagnetic field enhancement of closely spaced gold particles was greater than the loss due to increased resistance. The authors measured absorption and scattering of surface plasmons in rings of gold



**Ohmic heating and electric field distribution near gold nanoparticles in 1D self-assemblies.**

particles and found lower absorption and higher scattering efficiencies for coupled plasmons compared to surface plasmons of isolated particles. Because the results indicate that coupled surface plasmons in particle strings suffer smaller resistance losses compared with noninteracting collections of individual particles, the authors suggest that closely spaced metal particles could be used as amplifiers and antennas for functions including light-guides and biological sensors. — J.M.

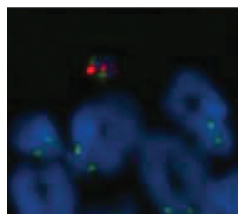
## Linux growth provides model for biological evolution

Modular software systems evolve into increasingly complex networks of interdependent subsystems. To meet their users' needs, computer operating systems must adapt to changing hardware environments while minimizing costs, in a manner that evokes biological evolution. Miguel Fortuna et al. (pp. 19985–19989) examined the changing modular network of dependencies that evolved during the first 10 releases of the Debian GNU/Linux operating system and identified analogies between it and ecological webs of interacting species. According to the authors, Debian GNU/Linux has become increasingly modular as it has grown, which minimizes the risk of system-wide collapse due the failure of individual software packages. Furthermore, with each successive release the newly added software packages predominantly exploited

preexisting, widely used subsystems, which has allowed Debian GNU/Linux to expand exponentially while decreasing conflicts between packages. This functional expansion via software creation and deprecation, the authors suggest, mirrors macroevolution in which speciation and extinction fine-tune increasingly complex biological networks. The findings demonstrate that further research into network evolution and self-assembly in engineered systems can provide opportunities for biologists and computer scientists to collaborate and study fundamental problems in biology, according to the authors. — T.J.

## Human artificial chromosomes for gene therapy

Small, engineered human artificial chromosomes (HACs) can act as new chromosomes in human cells. Unlike the viral vectors used in gene therapy, HACs avoid uncontrolled gene copy number and accidental gene mutation and silencing. Jung-Hyun Kim et al. (pp. 20048–20053) combined two recent HAC advances to “repair” human cells derived from patients with deficiencies in one of two cancer-associated genes. The researchers isolated the cancer-associated genes directly from the patients' genomic DNA, engineered a HAC carrying the genes, transferred the HAC into human cells, and observed that the inserted genes expressed proteins normally and complemented deficiencies in the patients' defective cells. In additional tests, the researchers were able to inactivate the HAC in the cell population, suggesting the method can be used to generate a control population of cells for researchers studying the effects of HAC-mediated cell therapies. Because HACs provide stable, reversible de-

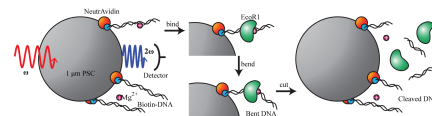


**Human artificial chromosome (red) carrying cancer-associated gene *NBS1*.**

livery of full-length genes into human cells, techniques based on HAC may be suitable for gene function studies and clinical gene therapy in the future, according to the authors. — J.M.

## Restriction enzyme–DNA interaction explored in real time

Most techniques to explore interactions between restriction enzymes and nucleic acids rely on the use of chemical labels, which can hinder an unobstructed view of the dynamics of enzyme reactions. Kenneth Eisenthal et al. (pp. 19979–19984)



**Restriction enzyme–DNA interaction explored.**

used a technique called time-resolved second harmonic spectroscopy to explore the reaction between EcoRI, a restriction enzyme commonly used in genetic engineering, and a 90 bp duplex of DNA attached to polystyrene carboxylate particles. Because the technique is sensitive to changes in the structure and electrical charge of molecules engaged in biological reactions, the authors could chart the progress of the reaction as a function of the second harmonic signal in real time. The binding of the enzyme to its recognition sequence in the DNA, the authors report, led to a change in the shape of the DNA—from rod-like to a bent conformation. The shape change triggered a spike in the second harmonic signal, which gradually dropped over hundreds of seconds, tracking the cleavage of the DNA, its dissociation from the enzyme, and its diffusion into the solution save a 16 bp fragment attached to the particle. The drop in the signal varied with the concentration of magnesium ions, which are crucial to the enzyme's function. According to the authors, the findings demonstrate the power of second harmonic spectroscopy to deconstruct biological reactions in real time with high sensitivity. — P.N.