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Separating Internal and External Dynamics of Complex Systems

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The observable behavior of a complex system reflects the mechanisms governing the internal interactions between the system's components and the effect of external perturbations. Here we show that by capturing the simultaneous activity of several of the system's components we can separate the internal dynamics from the external fluctuations. The method allows us to systematically determine the origin of fluctuations in various real systems, finding that while the Internet and the computer chip have robust internal dynamics, highway and Web traffic are driven by external demand. As multichannel measurements are becoming the norm in most fields, the method could help uncover the collective dynamics of a wide array of complex systems.

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Decades of research has lead to the development of sophisticated tools to analyze time series generated by various dynamical systems, allowing us to extract short and long range temporal correlations, periodic patterns, and stationarity information [1–4]. We lack, however, systematic methods to extract from multiple data sets information not already provided by a single time series. Indeed, advances in computer aided measurement techniques increasingly offer the possibility to separately but simultaneously record the time dependent activity of a system's many components, such as information flow on thousands of Internet routers or highway traffic on numerous highways. As the time dependent activity of each component (router or highway) captures the system's dynamics from a different angle, these parallel time series offer us increasingly complete information about the system's collective behavior. Yet, we have difficulty answering a simple question: How can we uncover from multiple time series a system's internal dynamics?

Multiple time series are typically available for complex systems whose dynamics is determined by the interaction of a large number of components that communicate with each other through some complex network [5]. The dynamics of each component is determined by two factors: (i) interactions between the components, governed by some internal dynamical rules that distribute the activity between the various parts of the system and (ii) global variations in the overall activity of the system. For example, the traffic increase on highways during peak hours and surges in the number of Internet users during working hours represent global activity changes that have a strong impact on the local activity of each component (highway or router) as well. Different components are influenced to a different degree by these global changes, making it impossible for an observer that has access only to a single component to separate the internal dynamics from the externally imposed fluctuations. Most important, the inevitable fluctuations in the external conditions systematically obscure the mechanisms that govern the system's internal dynamics.

Here we propose a method to separate in a systematic manner for each time series the external from the internal contributions, and validate it on model systems, for which the magnitude of the external perturbations can be explicitly controlled. By removing the impact of the external changes on the system's activity we gain insights into the internal dynamics of a wide range of systems, from Internet traffic to bit flow on a microprocessor.

Let us consider a dynamical system for which we can record the time dependent activity of N components, allowing us to assign to each component i a time series $\{f_i(t)\}$, $t = 1, \dots, T$ and $i = 1, \dots, N$. As each time series reflects the joint contribution from the system's internal dynamics and external fluctuations, we assume that we can separate the two contributions by writing

$$f_i(t) = f_i^{\text{int}}(t) + f_i^{\text{ext}}(t). \quad (1)$$

To determine $f_i^{\text{ext}}(t)$ let us consider the case when internal fluctuations are absent, and therefore the total traffic in the system is distributed in a deterministic fashion among all components. In this case, component i captures a time independent fraction A_i of the total traffic. For different components i , A_i can differ significantly, being determined by the component's centrality [6]. The challenge is to extract A_i from the experimentally available data without knowledge of the system's internal topology or the dynamical rules governing its activity. For this we write A_i as the ratio of the total traffic going through the component i in the time interval $t \in [0, T]$ and the total traffic going over all observed components during the same time interval

$$A_i = \frac{\sum_{t=1}^T f_i(t)}{\sum_{t=1}^T \sum_{i=1}^N f_i(t)}. \quad (2)$$

At any moment t the amount of traffic *expected* to go through node i is therefore given by the product of A_i and the total traffic in the system in moment t , providing the magnitude of the traffic expected if only external fluctuations contribute to the activity of node i as

$$f_i^{\text{ext}}(t) = A_i \sum_{i=1}^N f_i(t). \quad (3)$$

Equation (3) describes the case in which changes in the system's overall activity are reflected in a proportional fashion on each component. Real systems do display, however, internal fluctuations, which will generate local and temporal deviations from the expected $f_i^{\text{ext}}(t)$, a consequence of the internal time dependent redistribution of traffic in the system. Using (1)–(3) we obtain this internal component as

$$f_i^{\text{int}}(t) = f_i(t) - \left(\frac{\sum_{t=1}^T f_i(t)}{\sum_{t=1}^T \sum_{i=1}^N f_i(t)} \right) \sum_{i=1}^N f_i(t), \quad (4)$$

which, by definition, has zero average, as it captures the deviations from the traffic expected to go through component i . Given the experimentally measured dynamic signal $f_i(t)$ on a large number of components, (3) and (4) allow us to separate each signal $f_i(t)$ into two contributions, $f_i^{\text{ext}}(t)$ and $f_i^{\text{int}}(t)$, the first capturing changes in the system's overall activity, providing a measure of the external fluctuations, and the second describing the fluctuations characterizing the system's internal dynamics.

To test the ability of (3) and (4) to separate the internal and external components of a time series we investigate a simple model system of random walkers on a network [7]. We randomly displace M noninteracting walkers on the network, allowing each to perform N_s steps and monitor the total number of visitations f_i for each node i . If we repeat the experiment T times, we find that the number of visits to node i differs from one experiment to the other, the time series $\{f_i(t)\}$, $t = 1, \dots, T$ characterizing the fluctuations intrinsic to the diffusion process. If, however, we allow the number of walkers $M(t)$ to vary from one experiment to the other, the local variations in $f_i(t)$ are rooted not only in the random character of diffusion but also in variations imposed by changes in the total activity $M(t)$. An observer that records only a single $f_i(t)$ time series has difficulty deciding if the measured fluctuations reflect the system's internal dynamics only or some non-stationary external effect. To test the method's ability to separate the internal and external fluctuations we use an external signal with an easily recognizable periodic profile $M(t) = \langle M \rangle + \Delta M \sin(kt)$. Figures 1(a) and 1(d) show the activity $f_i(t)$ recorded for a typical node for two different ΔM amplitudes, representing a visible superposition of the sinusoidal external signal and the internal randomness of the diffusion process. As Figs. 1(b) and 1(e) show, the external component provided by (3) fully recovers the external signal imposed on the system. After removing the external component using Eq. (4) we obtain a random pattern reflecting the intrinsic fluctuations of the diffusion process. The method works equally well in the case when the magnitude of the external fluctuations is large [Fig. 1(a)] or small [Fig. 1(d)] compared to the system's internal fluctuations [8].

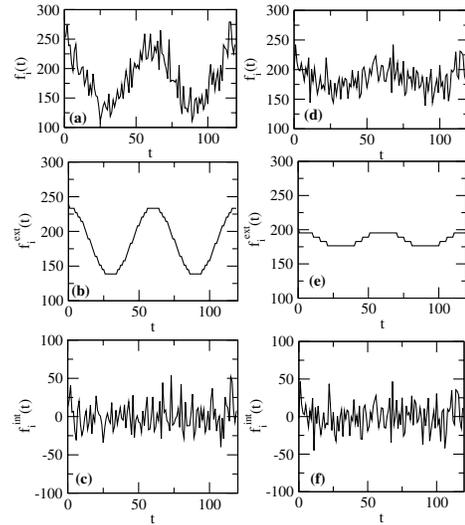


FIG. 1. Splitting a measured signal into its external and internal contributions for the model system. We study the traffic on the nodes of a scale-free network with 10^3 nodes, generated by $M(t)$ random walkers whose number follow a sinusoidal signal with amplitude ΔM and period 60. (a) The activity measured on a typical node when the amplitude of the external fluctuations is $\Delta M = 1000$. (b) The external contribution provided by Eq. (3) recovers the periodic signal imposed on the system. (c) The internal contribution, predicted by Eq. (4), captures the random pattern of the diffusion process. (d)–(f) The same as in (a)–(c) but with a small external amplitude $\Delta M = 10$, demonstrating that the method works even when the amplitude of external fluctuations are comparable to fluctuations of the internal dynamics.

We can use (3) and (4) to determine if the fluctuations observed in a system are mainly internally or externally imposed. For each recorded signal i we determine the external and internal standard deviations, $\sigma_i^{\text{ext}} = \sqrt{\langle f_i^{\text{ext}}(t)^2 \rangle - \langle f_i^{\text{ext}}(t) \rangle^2}$ and $\sigma_i^{\text{int}} = \sqrt{\langle f_i^{\text{int}}(t)^2 \rangle - \langle f_i^{\text{int}}(t) \rangle^2}$, and their ratio

$$\eta_i = \frac{\sigma_i^{\text{ext}}}{\sigma_i^{\text{int}}}. \quad (5)$$

When $\eta_i \gg 1$, the external fluctuations dominate the dynamics of component i , while for $\eta_i \ll 1$ the system's internal dynamics dominates over the externally imposed changes. As different signals have different η_i values, the system's overall behavior is best characterized by the $P(\eta_i)$ distribution, obtained after calculating η_i for each signal we have access to. Figures 2(a) and 2(b) show $P(\eta_i)$ for the random walk model, in which the number of walkers follows $M(t) = \langle M \rangle + \xi_i(t)$, where $\xi_i(t)$ is a random variable uniformly distributed between $-\Delta M/2$ and $\Delta M/2$. For small external fluctuations ($\Delta M \approx 0$), the $P(\eta_i)$ distribution is highly peaked and is located entirely in the $\eta_i \ll 1$ region, indicating that external fluctuations have little influence on the dynamics of the individual components. For high ΔM , however, $P(\eta_i)$ lies in the

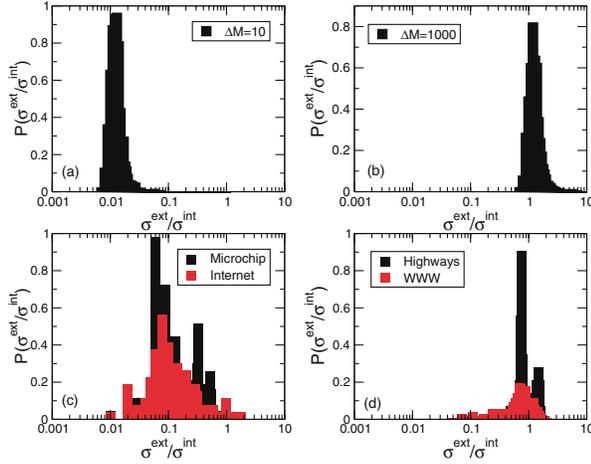


FIG. 2 (color online). Distribution of $\eta_i = \sigma_i^{\text{ext}}/\sigma_i^{\text{int}}$ ratios of external and internal fluctuations for model (a),(b) and selected real systems (c),(d). Distribution of the η_i ratios for the random walk model: (a) For smaller external fluctuations, the distribution is centered around a small value of $\eta \ll 1$, indicating that internal fluctuations overcome external ones, dominating the system's dynamics. (b) When ΔM is increased, however, such fluctuations overshadow the system's internal dynamics, and the $P(\eta)$ distribution shifts towards larger values of η . (c) $P(\eta)$ distributions for the Internet and the microchip, centered around $\eta \sim 0.1$, indicate that external fluctuations do not affect the system's overall dynamics significantly. (d) The World Wide Web and the highway networks, with $P(\eta)$ peaked around $\eta \sim 1$, are strongly influenced by fluctuations in the total number of web surfers and the number of cars, respectively.

$\eta \geq 1$ region, indicating that the system's dynamics is dominated by external fluctuations.

Our ability to split the time series into an internal and external signal offers novel insights into the dynamics of four systems of major technological importance: Internet routers [9], a microchip [10], the World Wide Web (WWW) [11], and the highway system of Colorado. We collected time resolved information about the activity of a large number of components, such as traffic on 374 Internet routers, switching behavior of 462 gates of a microchip, the daily visitations of 3000 web sites on the Web, and the daily traffic for 127 highways in Colorado (details about the databases are provided in Ref. [7]). We used (1)–(4) to separate the signal for each component i , the corresponding $P(\eta)$ distribution unraveling clear differences between the studied systems. We find that for the Internet and the microchip internal fluctuations dominate over the externally induced changes, as the $P(\eta)$ distribution lies in the $\eta \ll 1$ region, peaked around $\eta \simeq 0.08$ [Fig. 2(c)]. On the other hand, for the World Wide Web and highways the typical η ratios are an order of magnitude larger [Fig. 2(d)], the $P(\eta)$ distribution being peaked at $\eta \simeq 1$, indicating that for these two systems the external and internal fluctuations are comparable in magnitude.

This separation correlates with the finding that the four studied systems belong to two distinct universality classes [7]. Indeed, for each recorded signal the time

average $\langle f_i \rangle$ and the standard deviation σ_i obey the scaling law $\sigma_i \sim \langle f_i \rangle^\alpha$, where for the microchip and the Internet $\alpha = 1/2$, while for the highways and the WWW $\alpha = 1$. Figure 2 indicates that α correlates with the relative magnitude of the external fluctuations [7]: for systems with $\alpha = 1/2$ the internal fluctuations dominate [Fig. 2(c)], while for systems with $\alpha = 1$ the impact of the external fluctuations is at least comparable to the fluctuations generated by the system's internal dynamics [Fig. 2(d)].

The $P(\eta)$ distribution tells us only the origins of the fluctuations and is not sufficient to understand the intimate differences between the internal and the external contributions. A more detailed understanding is provided by plotting for each signal i the σ_i^{ext} and the σ_i^{int} standard deviations in function of the average $\langle f_i \rangle$ [Figs. 3(a)–3(d)]. We find that for the microchip and the Internet σ_i^{ext} and σ_i^{int} scale with different exponents [Figs. 3(a) and 3(b)]: the internal fluctuations scale with $\alpha = 1/2$, while the external signal scales with $\alpha = 1$ (which is an expected feature of the external fluctuations [7]). Furthermore, for these two systems the internal standard deviation is much larger than the external one [$\sigma_i^{\text{int}}(\langle f_i \rangle) \gg \sigma_i^{\text{ext}}(\langle f_i \rangle)$], explaining why the overall $\sigma \sim \langle f \rangle^\alpha$ scaling captures only the $\alpha = 1/2$ exponent. In contrast, for the WWW and the highways the σ_i^{ext} and σ_i^{int} curves overlap, both following the $\alpha = 1$ exponent [Figs. 3(c) and 3(d)].

The qualitative difference between the two sets of plots in Fig. 3 reflects fundamental differences in the internal dynamics of the four studied real systems. The splitting of the curves seen in Figs. 3(a) and 3(b) indicates that the

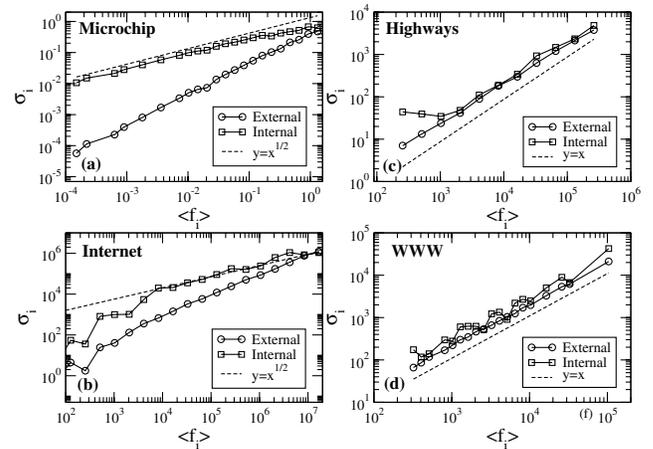


FIG. 3. Scaling of the external and internal fluctuations with the average flux. Internal fluctuations σ_i^{int} on the microchip (a) and on the Internet (b), both belonging to the $\alpha = 1/2$ class, are significantly larger than external fluctuations σ_i^{ext} and scale with a different exponent. External and internal fluctuations are comparable in magnitude on the World Wide Web (c) and the highway network (d), and they also follow the same scaling, indicating that in these systems' external fluctuations should have strong impact on systems' overall dynamics.

Internet and microchip are characterized by a robust internal dynamics, which leads to a dominating $\alpha = 1/2$ internal scaling. While the $\alpha = 1/2$ exponent emerges in the studied diffusion model as well [7], the nature of the internal dynamics and the origin of the $1/2$ exponent needs to be addressed in each system separately. In contrast, the overlapping curves seen in Figs. 3(c) and 3(d) indicate not only that highway and WWW traffic are much more susceptible to external perturbations but also suggest that these systems do not have a clearly separable internal dynamics. That is, the local activity of the system is driven simply by global demand, and the interactions between the various highways or web sites do not lead to a distinguishable internal dynamics. Indeed, while on the microchip and on the Internet there are strict protocols regulating the traffic of bits or packages, highways and the WWW allow for a much higher flexibility, the users having the option to leave the system each time they encounter unfavorable local conditions, such as highway congestion or Web delays. Yet, highway and Internet traffic in many ways are quite similar [12,13], each describing a clear source-destination shortest-path traffic. Thus, the fundamental difference in their internal dynamics is in many ways surprising and warrants further inquiry.

Our simulations indicate that a nonstationary external noise does not affect the method's applicability, as the nonstationary behavior will be carried by the external component of the separated signal. However, it is unclear if the method could be applied if there is internal nonstationarity in the system, corresponding to time dependent shifts in the system's overall activity between groups of nodes. Such internal nonstationarity can be uncovered by calculating the A_i parameters in nonoverlapping time windows [14], potentially resulting in significant lasting shifts in the A_i values. An inspection of the four studied systems did not reveal nonstationary internal behavior, the A_i parameter fluctuating around $\langle A_i \rangle$. The method appears to be insensitive to the choice of the observational window T used in Eq. (2), as long as T is large enough so that the average can be evaluated.

In an increasing number of complex systems one can experimentally monitor the simultaneous activity of hundreds of channels, examples including multichannel measurement of neural activity on *in vivo* cell colonies [15], simultaneous monitoring of thousands of gene expression data sets for model organisms such as *E. Coli* or *S. Cerevisiae* [16], flow fluctuation in river networks [3,17], price variations in individual stocks or goods [18], or the activity of different processors in parallel computation [19]. The method introduced here represents a systematic tool for extracting information from multiple channel measurements, offering detailed insights into the mechanisms that govern the dynamics of these systems.

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