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Dynamics of Ranking Processes in Complex Systems

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(Received 6 April 2012; published 17 September 2012)

The world is addicted to ranking: everything, from the reputation of scientists, journals, and universities to purchasing decisions is driven by measured or perceived differences between them. Here, we analyze empirical data capturing real time ranking in a number of systems, helping to identify the universal characteristics of ranking dynamics. We develop a continuum theory that not only predicts the stability of the ranking process, but shows that a noise-induced phase transition is at the heart of the observed differences in ranking regimes. The key parameters of the continuum theory can be explicitly measured from data, allowing us to predict and experimentally document the existence of three phases that govern ranking stability.

DOI: 10.1103/PhysRevLett.109.128701 PACS numbers: 89.75.Hc, 64.60.al, 05.10.Gg, 05.40.–a

Some rankings, such as best-seller lists or trends measured by Twitter and Wikipedia, are intrinsically volatile, changing daily; others, such as intellectual achievement, show remarkable stability, keeping Darwin and Einstein as the most frequently mentioned scientists in the past 50 years [1–3]. These different patterns of ranking stability are illustrated in Fig. 1, which indicate that the has been the most frequently used English word in printed texts for at least 200 years [Fig. 1(a)]. In contrast, the ranking of research papers based on their citation patterns [Fig. 1(b)] displays significant volatility over time (see Fig. S10 for more examples [4]). While the items at the top of each list command high visibility, relatively little scientific attention is devoted to the rules and regularities of the ranking process itself. There is a good reason for this: rankings span such diverse areas, each with its own driving forces and peculiarities, that it appears to be a hopeless exercise to seek order in such a diverse subject. For example, the failures of existing models to capture the rank dynamics of companies [5], the number of diagnoses of a particular disease recorded in Medicare during a month [7], the number of annual citations each paper received in the Physical Review corpus [1,8,9], the number of times a particular hashtag was used in tweets during a day [10,11], and the number of hourly page views of articles in Wikipedia [12] (Table S1). The temporal resolution of the data varies from hours to years and the time span from days to centuries.

The cumulative distribution of the market share of each item, P(x), indicates that x spans orders of magnitude (Fig. S11). In some systems, P(x) follows a clear power law (word usage, Twitter), while in others we observe cutoffs at high x (market cap, Medicare); P(x) can be stationary or may shift in time. Despite these differences, changes in the market share of individual items follow a universal pattern [Figs. 1(c), 1(d), and S10e–h]. Indeed, we
fluctuations appear to correlate with ranking stability. This scatter plot of and 1(b). [13,14] may contribute to the stability of the high-ranked items, where the volatility of large companies is less than that of low-ranked items, which is known in the economic context, implying that relative changes are typically smaller for top-ranked items.

FIG. 1 (color online). Empirical characteristics of ranked systems. (a),(b) The evolution of the ranks of five top items in two systems: word usage displays ranking stability, and citation shows significant volatility. (c),(d) Surface plot of in a function of , indicating that for each system the dispersion of fluctuates symmetrically around . While is comparable for all systems, we observe a remarkable asymmetry for high . For citation, similar data for systems: word usage displays ranking stability, and citation.

Next, we show that the observed differences in are significant. While is comparable for all systems, we observe significant differences in the magnitude of the coefficient : for systems with stable ranking, we find ; while, for the systems with unstable ranking, we observe (Table S1). Since the coefficient is a direct measure of the noise magnitude, we find that the three unstable systems are affected by a higher level of noise than the three stable systems. Note that the difference between the two classes is independent of (see Sec. S3 and Fig. S12).

Next, we show that the observed differences in can induce a noise-driven phase transition in ranking, offering a quantitative explanation of the documented differences in ranking stability. Denoting by the probability of an item to have score at time given its fitness , the temporal evolution of is governed by the Fokker-Planck equation

\[
\frac{\partial P(x_t, t|A)}{\partial t} = - \frac{\partial}{\partial x} \left( f(x_t) P(x_t, t|A) \right) + \frac{1}{2} \frac{\partial^2}{\partial x^2} \left( g(x_t) \sigma^2(x_t, t|A) P(x_t, t|A) \right).
\]

This choice is directly inspired by the measurements (2) [Figs. 1(c) and 1(d)], since the variance of score variations can be expressed as and (see Eq. S5).

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We make two simplifying assumptions, suggested by empirical data. First, we postulate that the drift term can be written as

\[
f(x_t) = A_i x_t^\alpha,
\]

where and is identical for all .

We also assume the intrinsic ability to increase its market share .

The second term captures the inherent randomness in the system; hence, can be interpreted as the “fitness” of item , capturing a wide range of system-dependent attributes, from utility (words) to information content (Wikipedia) or impact (research papers), together with the relative fitness of each item compared to its peers.

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where
\[ x_c = \left( \frac{A_i}{\phi_0} \right) ^ \gamma \left( \frac{2(1-\beta)}{1+\alpha-2\beta} \right) \gamma \approx \frac{1}{1-\alpha}, \tag{8} \]
and \( C(A_i) \) is the normalization constant.

To find the most probable value of \( x_i \), we set the derivative of Eq. (7) to zero, obtaining

\[ F(x_i) = (Ax_i^\mu - \phi_0 x_i) - \frac{B^2}{\beta} x_i^{2\beta-1} = 0. \tag{9} \]

For \( B = 0 \), the solution of Eq. (9) is

\[ x_i^* = \left( \frac{A_i}{\phi_0} \right) ^ \gamma. \tag{10} \]

One can obtain Eq. (10) directly from the steady-state solution of Eq. (3) with \( f(x_i) \) defined in Eq. (4) and \( g(x_i) = 0 \). Equation (10) indicates that each item will converge to a score determined by its fitness \( A_i \) and a combination of all other fitnesses via \( \phi_0 = \langle \sum A_i^\gamma \rangle ^ {1/\gamma} \).

In the presence of noise, Eq. (9) indicates that \( B \) shifts the steady-state value of \( x_i \) from its deterministic solution \( x_i^* \) to a new \( x_i^* + \delta_i \). Equation (9) predicts that changes in the noise magnitude \( B \) induce a dynamical phase transition from a stable (confined) score to an unstable (delocalized) score phase. For \( B < B_c \), Eq. (9) has two solutions, at \( x_i = x_i^* + \delta_i \) (stable) and \( x_i = 0 \) (unstable) (Fig. S13b). Therefore, \( P(x_i|A_i) \) is unimodal with a sharp peak (Fig. S13c), indicating that for low noise the market share of item \( i \) will be localized around a value determined by the interplay between the item’s fitness and the noise magnitude. At \( B = B_c \), the nonzero solution disappears ((\( x_i = x_i^* + \delta_i \) \( \rightarrow \) 0; see Figs. S13c and S13f). Equation (7) predicts that for \( B > B_c \) the distribution follows a power law \( P(x_i|A_i) \approx x_i^{-2\beta} \) with an exponential cutoff at high \( x_i \). This implies that \( x_i \) is no longer confined to the vicinity of \( x_i^* \) but becomes delocalized, varying over orders of magnitude.

The consequence of the predicted noise-induced phase transition is illustrated in Figs. S13h–j, where we show the evolution of the ranks for the top five fitness items, as predicted by numerical simulations of Eq. (3). In the stable phase \( B < B_c \), the top items maintain their nominal rank, determined by their respective fitnesses, similar to the behavior observed in Fig. 1(a). At the critical point \( B = B_c \), the stable ranking is perturbed by unstable bursts, an intermittent behavior common in dynamical systems at the critical point \([17,18]\). Finally, for \( B > B_c \) most items become delocalized, lacking rank stability, a behavior similar to the one observed in Fig. 1(b).

To further test the predictive power of our model in Fig. S13, we plot the average change in score \( \langle \Delta x \rangle \) and \( \sigma_{\Delta x} \) as a function of the score \( x \). For \( B < B_c \), the score variation \( \Delta x \) fluctuates symmetrically around \( \Delta x = 0 \), similar to the behavior observed in stable systems [Fig. 1(e)]. For \( B > B_c \), however, there is a systematic downward trend for high \( x \), as observed for the unstable systems [Fig. 1(f)]. Indeed, while a precise empirical determination of the drift term is difficult, the choice of its functional form Eq. (4) is supported by the qualitative agreement between Figs. 1(e), 1(f), S13k, and S13m.

Score stability, the expectation that \( x_i \) fluctuates around a well-defined mean, is a necessary but not a sufficient condition for an item to maintain a stable rank. Rank is a collective measure: it depends not only on the score \( x_i \) of item \( i \), but also the score of all other items \( j (\neq i) \) to which \( x_i \) is compared. While an item may be score-stable, its fluctuation around \( x_i^* \) may be sufficiently large so that \( P_0(x_i|A_i) \) for items with comparable \( x_i^* \) may overlap and thus the items can swap ranks, a phenomenon akin to the melting of a solid, where atoms cannot remain in register due to thermal agitation. Score (and rank) stability can occur only in the \( B < B_c \) regime, and a saddle point approximation provides the magnitude of the fluctuations in \( x_i \) around its steady-state market share \( x_i^* \) (see Sec. S2.1). Assuming that the intrinsic fitnesses \( A_i \) are drawn from \( P(A) \sim A^{-1+\mu} \) (see Fig. S11 for empirical support), we can relate the rank fluctuation of an item to its rank \( r \) (Eq. S21 and [9]):

\[ \sigma_r = \left( \frac{\gamma}{2\phi_0} \right)^{1/2} B(x_r)^{\beta}. \tag{11} \]

For an item to show rank stability, the inequality \( \Delta_r = \langle x_r \rangle - \langle x_r \rangle _{r+1} > \sigma_r \) predicts a second critical value of the noise coefficient, \( B_r < B_c \), controlling rank stability (where \( \langle x_r \rangle \) is the expected score of an item with rank \( r \)).

These results indicate that the stability of a list is best captured by the \( A-B \) phase diagram shown in Fig. 2(a). The top part \( (B > B_r) \) is the unstable region, where Eq. (7) predicts that the score of each item is broadly distributed; hence, neither rank nor score stability is possible, similar to a gas phase where atoms move at random. In the region \( B < B_r \), we have score stability, which means that each score fluctuates around a steady-state market share \( x^* \) determined by its intrinsic fitness. Yet, score stability does not necessarily imply rank stability. Hence, there are two distinct phases below \( B_r \): a score-stable (liquid) phase between \( B_c \) and \( B_r \), where each item has a stable score but the fluctuations around \( x^* \) are sufficient for items with comparable score to swap rank. For \( B \) below \( B_r \), we find a solid phase: the noise is sufficiently low so that items
Our theory predicts that for score-stable systems the market share of the top-ranked items varies over 3–4 orders of magnitude, in line with the fat tailed form (9) predicted for this region.

display not only score but also rank stability. These predictions are supported by Fig. 2(b), where we plot the time evolution of ranks for the top items in each phase.

In the phase diagram of Fig. 2(a), we can represent each real system with a horizontal line placed at its experimentally measured \( B \) (Table S1). Medicare, word usage, and market cap are deep in the rank-stable regime, indicating that highly ranked items should display rank stability, a prediction that agrees with the empirical results of Figs. 1(a) and S10. An order of magnitude gap in \( B \) separates them from the three unstable systems, Twitter, Wikipedia, and citation, that are deeply in the unstable phase.

Our theory predicts that for score-stable systems the market share \( x_i \) of the high-fitness items should be narrowly distributed, in contrast with the unstable phase, where \( x_i \) fluctuates widely [Fig. 2(c)]. We therefore measured \( P(x_i) \) for top-scoring items in each system [Fig. 2(d)], finding that, as expected, in the three stable systems \( P(x_i) \) is narrow, spanning less than an order of magnitude. In contrast, for the three unstable systems \( P(x_i) \) spans 3–4 orders of magnitude.

Taken together, our results indicate that the ranking stability observed in some systems and the volatile ranking observed in others represent different phases separated by a noise-induced phase transition. Despite the diversity of the explored systems, their dynamics can be qualitatively captured by a single continuum theory that predicts the existence of three dynamically distinct phases. In analogy with critical phenomena, one could view \( B \) as the control parameter and the score’s standard deviation as the order parameter.

With suitable enrichments—for example, through the incorporation of fads and herding [19,20]—the introduced formalism may be extendible to a wider range of systems such as biodiversity and linguistics [21,22]. A detailed account should also consider the role of memory and correlations (see Secs. S6 and S7 for results on this). In our formalism, we take into account global shocks [23], since \( \phi(t) \) enforces normalization. Local correlations, present for related items, could reduce the relative motion between items, increasing rank stability. Such stability could shift the rank-stable transition upwards in Fig. 2. Remarkably, the model qualitatively emulates correlations observed in the data even without explicitly enforcing local correlations (Figs. S1 and S2).


