

Impact of single links in competitive percolation

Jan Nagler^{1,2*}, Anna Levina^{1,3} and Marc Timme^{1,2,3}

How a complex network is connected crucially impacts its dynamics and function. Percolation, the transition to extensive connectedness on gradual addition of links, was long believed to be continuous, but recent numerical evidence of ‘explosive percolation’ suggests that it might also be discontinuous if links compete for addition. Here we analyse the microscopic mechanisms underlying discontinuous percolation processes and reveal a strong impact of single-link additions. We show that in generic competitive percolation processes, including those showing explosive percolation, single links do not induce a discontinuous gap in the largest cluster size in the thermodynamic limit. Nevertheless, our results highlight that for large finite systems single links may still induce substantial gaps, because gap sizes scale weakly algebraically with system size. Several essentially macroscopic clusters coexist immediately before the transition, announcing discontinuous percolation. These results explain how single links may drastically change macroscopic connectivity in networks where links add competitively.

Percolation, the transition to large-scale connectedness of networks on gradual addition of links, occurs during growth and evolutionary processes in a large variety of natural, technological and social systems^{1–6}. Percolation arises in atomic and molecular solids in physics as well as in social, biological and artificial networks^{2,7–10}. In the more complex of these systems, adding links often is a competitive process. For instance, a human host carrying a virus may travel at any given time to one but not to another geographic location and therefore infect other people only at one of the places^{11,12}. Across all percolating systems, once the number of added links exceeds a certain critical value, extensively large connected components (clusters) emerge that dominate the system.

Given the breadth of experimental, numerical and empirical studies, as well as several theoretical results and analytic arguments^{13–16}, percolation was commonly believed to exhibit a continuous transition where the relative size of the largest cluster increases continuously from zero in the thermodynamic limit once the number of links crosses a certain threshold. Therefore, recent work by Achlioptas, D’Souza and Spencer¹⁷ came as a surprise because it suggested a new class of random percolating systems that exhibit ‘explosive percolation’¹⁸. Close to some threshold value, the system they considered shows a steep increase of the largest-cluster size on increasing the number of links; moreover, numerical scaling analysis of finite-size systems suggests a discontinuous percolation transition. This study initiated several follow-up works (for example refs 10,19–26) confirming the original results for a number of system modifications. These in particular support that competition in the addition of links is crucial; the key mechanisms underlying discontinuous percolation, however, are still not well understood. Although some works have considered single-link addition processes^{22,27} the impact of individual link additions on competitive percolation transitions is unknown.

Gaining one or a few links may have drastic consequences for a network’s growth and its overall dynamics, depending on whether or not such individual links qualitatively alter the global connectivity of a network. For instance, spontaneous

activity in developing neural circuits may become persistent after establishing some extra synaptic connections^{28,29}. Similarly, during beginning pandemics the specific travel patterns of a single infected person may substantially change the number of infecteds on a timescale of months¹¹.

Here we identify how microscopic single-link additions impact competitive processes. We find that, in generic percolation processes, single links do not induce macroscopic gaps in the largest cluster size as the system size $N \rightarrow \infty$. Nevertheless, the gap sizes decay weakly algebraically as $N^{-\beta}$ with often small β such that gaps are essentially macroscopic, that is, substantially large even for systems of macroscopic size $N \approx 10^{23}$. Such gaps, induced by single links, occur at the point of percolation transitions, are a key signature of discontinuous percolation and are announced by several coexisting, essentially macroscopic clusters.

How discontinuous are the transitions?

Consider a family of competitive percolation processes where potentially new links compete with others for addition (Fig. 1). Starting with an empty graph of a large number N of isolated nodes (no links), links sequentially add in competition with others. For edge competition, for each single-link addition, m potential links are randomly selected. The link for which the sum of the sizes of the clusters containing its two end-nodes is smallest wins the competition and adds. Intra-cluster links are possible; these can only broaden the transition compared with disallowing them. For $m = 1$, this process is non-competitive and identical to random Erdős–Rényi percolation¹⁴, whereas for $m = 2$ it specializes to the process introduced before¹⁷. For all $m \geq 2$, this kind of competition promotes that during gradual addition of links smaller clusters tend to be connected (to form larger ones) before larger clusters grow. With increasing m , the process becomes more strongly competitive, because more potentially new links actually compete. If m is maximal, all potential links in the network compete for addition and we have global competition.

Taking the sum of cluster sizes in edge competitive processes seems somewhat arbitrary because, for example, taking the

¹Max Planck Institute for Dynamics and Self-Organization (MPI DS) Göttingen, Bunsenstr. 10, 37073 Göttingen, Germany, ²Institute for Nonlinear Dynamics, Faculty of Physics, University of Göttingen, Bunsenstr. 10, 37073 Göttingen, Germany, ³Bernstein Center for Computational Neuroscience (BCCN) Göttingen, Bunsenstr. 10, 37073 Göttingen, Germany. *e-mail: jan@nld.ds.mpg.de.

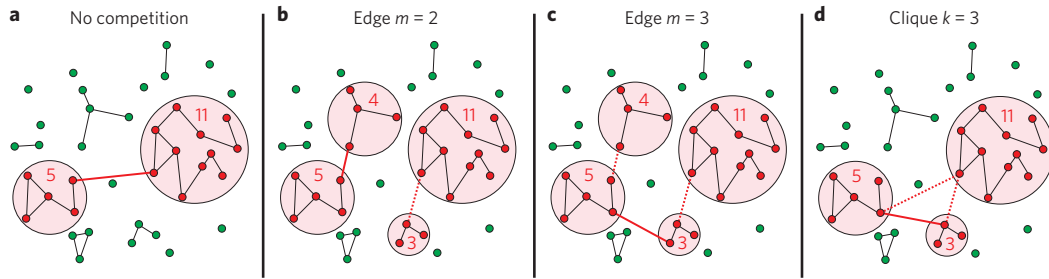


Figure 1 | Competitive versus non-competitive percolation processes. **a**, Non-competitive Erdős-Rényi percolation: new links are randomly chosen and just add. **b**, Edge competition: $m = 2$ links compete with each other and clusters of sizes 4 and 5 win the competition and join to form a new cluster of size 9. **c**, $m = 3$ links compete with one another. Clusters of sizes 3 and 5 join. **d**, Clique competition ($k = 3$): three links within a clique compete. Clusters of sizes 3 and 5 join. Throughout all panels, small discs indicate nodes; solid black lines indicate existing links; large shaded discs indicate clusters entering the competition with numbers denoting their sizes; red dashed lines indicate potentially new, competing links; solid red lines indicate actual links added.

product³⁰, or, for that matter, any convex function of the two cluster sizes, has similar competitive effects; compare ref. 17. We thus consider also clique competition, which does not suffer from this ambiguity. For clique competition, we randomly draw a fixed number k of nodes and connect those two of them contained in the two smallest clusters. Here $k = 2$ describes non-competitive random percolation and for all $k \geq 3$ competition has the same principal effect on changes in cluster sizes as edge competition; compare refs 23,26 for the special case $k = 3$. We remark that for maximal possible k we again have global competition.

For large finite systems, single realizations of genuinely competitive processes ($m \geq 2$ or $k \geq 3$; compare Fig. 2) exhibit macroscopic $\mathcal{O}(N)$ changes in the size C_1 of the largest cluster C_1 . In fact, numerical scaling studies (Supplementary Fig. S1) confirm that the transition regime in the plane spanned by $\ell = L/N$ and $c_1 = C_1/N$ shows an $\mathcal{O}(1)$ change of c_1 in a region of width $\Delta\ell$ that scales as $N^{-\gamma}$, $\gamma > 0$, for large N (compare also ref. 17). These results may suggest that in the limit of infinite systems there is a discontinuous $\mathcal{O}(1)$ gap in the curve characterizing competitive percolation in the $\ell - c_1$ plane.

Further investigating the microscopic dynamics of the transition, however, seeds doubt about any such gap. If the largest gap $\Delta C_{\max} := \max_L (C_1(L+1) - C_1(L))$ is macroscopic (extensive),

$$\lim_{N \rightarrow \infty} \frac{\Delta C_{\max}}{N} > 0 \quad (1)$$

we call such transitions strongly discontinuous, otherwise weakly discontinuous (see Supplementary Information for an exact definition). For weakly discontinuous transitions, the curve in the $\ell - c_1$ plane does in fact not exhibit any such macroscopic gap for a single-link addition in the thermodynamic limit.

Evaluating the largest jump size ΔC_{\max} from extensive numerical simulations of systems up to size 2^{22} already suggests (Fig. 3) that it scales algebraically as

$$\frac{\Delta C_{\max}}{N} \sim N^{-\beta} \quad (2)$$

independent of whether the process is non-competitive, minimally competitive ($k = 3, m = 2$) or exhibits even stronger forms of competition ($k \geq 4, m \geq 3$). As we find that $\beta > 0$ for all such processes, we have $\lim_{N \rightarrow \infty} \Delta C_{\max}/N = 0$ and thus the transitions are all weakly discontinuous. The only exception seems to be global competition, where we find β indistinguishable from zero and $\Delta C_{\max}/N \approx 0.5 > 0$ for all N , indicating a strongly discontinuous transition, equation (1). The set of all numerical analyses therefore suggests that competitive percolation transitions are generically weakly discontinuous, and single links do not induce a gap in c_1

in the thermodynamic limit $N \rightarrow \infty$. Nevertheless, as the gap sizes scale weakly algebraically with system size (2) with often small β such gaps may still be essentially macroscopic, that is, substantially large even for macroscopic systems of large finite size N .

The impact of single links

So how can single links actually impact the dynamics of the transition? For the extreme case of global competition, exact analytical arguments reveal the occurrence of macroscopic jumps and give key insights about the nature of transitions in competitive percolation processes, that similarly hold for weakly discontinuous transitions (see below). We label all existing clusters by C_i and their sizes by $C_i = |C_i|$ where the index i labels their size rank such that $C_1 \geq C_2 \geq \dots \geq C_{\nu_{\max}}$ where $\nu_{\max} \leq N$ denotes the total number of existing clusters. For global competition each newly added link joins the two smallest clusters in the entire system such that $C_{\nu_{\max}} + C_{\nu_{\max}-1} \rightarrow C'$. For simplicity of presentation, we choose the system size N to be a power of 2. This ensures that up to $L_1 = N/2$ new links only connect 1-clusters (isolated nodes) to result in new 2-clusters (two nodes with a single connecting link) such that the maximum cluster size remains $C_1 = 2$ for all $L \leq L_1$. The subsequent $N/4$ links each connect 2-clusters to 4-clusters, keeping $C_1 = 4$ until $L_2 = 3N/4$. In general, new links added between L_{n-1} and L_n connect 2^{n-1} -clusters to 2^n -clusters, keeping

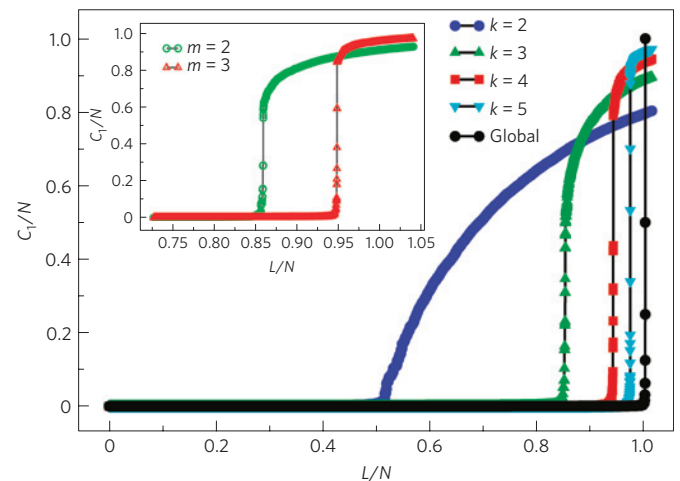


Figure 2 | Dynamics of largest cluster size in competitive percolation processes. Growth of C_1 as a function of the number of added links L for non-competitive ($k = 2$), competitive and globally competitive percolation processes for both edge (inset) and clique competition (main panel); $N = 2^{16}$ nodes, quantities on both axes rescaled by system size N . A single realization is shown for each percolation process.

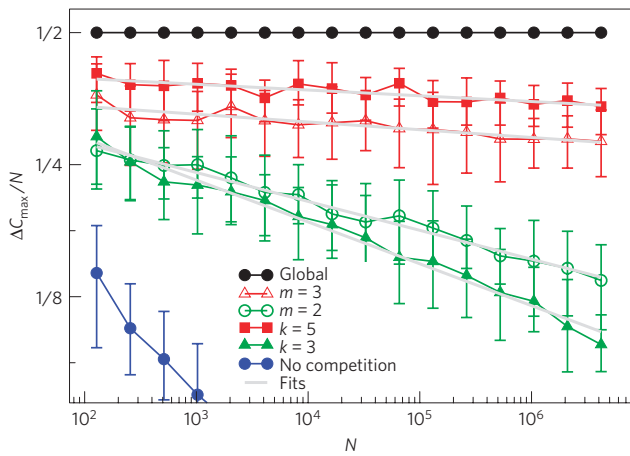


Figure 3 | Gap sizes ΔC_{\max} decay algebraically with system size N for weakly discontinuous transitions. Green symbols, weakest competition; red symbols, stronger competition; black symbols, global competition; blue symbols, no competition ($k = 2, m = 1$). The symbols indicate averages over 50 realizations; error bars indicate 25% quantiles and reflect system-intrinsic fluctuations. Solid grey lines are best least-square fits (slopes, $\beta = 0.013$ ($k = 5$), $\beta = 0.018$ ($m = 3$), $\beta = 0.065$ ($m = 2$) and $\beta = 0.095$ ($k = 3$)). The black line shows the analytical curve for global competition, where $\beta = 0$.

$C_1 = 2^n$ where $L_n = ((2^n - 1)/2^n)N$, for all $n \leq \log_2(N)$. In the final step, at $L = N - 1$, the remaining two $N/2$ -clusters join and induce the largest gap

$$\frac{\Delta C_{\max}}{N} = \frac{1}{2} \tag{3}$$

analytically confirming the numerical findings (Figs 2 and 3). As a consequence, global competition (involving information about the entire system’s state for local link addition) implies a genuine gap of size $1/2$ in the main order parameter c_1 .

For weaker forms of competition, closely related link-adding mechanisms control the cluster joining dynamics. Inspecting the impact of single-link additions on cluster joining dynamics in more detail, we identify three distinct mechanisms that may contribute towards increasing the size C_1 of the current largest cluster in more general competitive processes. (i) Direct largest-cluster growth: the largest cluster itself connects to a smaller cluster of size $C_i < C_1$ and grows, $C_1 + C_i \rightarrow C_1$, to stay the largest cluster. (ii) Overtaking: two smaller clusters of size $C_i, C_j < C_1$ join into one that is larger than the current largest cluster, $C_i + C_j \rightarrow C_1$, and the originally largest cluster becomes second largest, $C_1 \rightarrow C_2$. (iii) Doubling: if there are several clusters of maximal size $C_1 = C_2 = \dots = C_\nu$, for some $\nu \geq 2$, two of these join, $C_i + C_j \rightarrow C_1$ for some $i, j \in \{1, \dots, \nu\}$, creating a new largest cluster of twice the size of the original one.

For each single-link addition, we denote the probability for direct cluster growth (i) by p_{gr} . We say that $p_{gr} = 0$ if the probability of direct growth of the largest cluster (i) is zero up to the point where only two clusters are left in the system and direct growth is the only remaining way the largest cluster could grow at all (see Supplementary Information for a more formal definition).

As we show in the following, an arbitrary percolation process with $p_{gr} = 0$ necessarily exhibits a genuine gap and thus a strongly discontinuous transition, that is $\Delta C_{\max}/N$ stays positive in the limit of infinitely large system sizes N . As growth (i) is prohibited, the largest-cluster size changes either by overtaking (ii) or by doubling (iii). During any such percolation process adding a link never more than doubles C_1 . As a consequence, there is a certain L' such that $C_1(L')$ is larger than $N/3$ but not larger than $2N/3$. When C_1 will

be overtaken (or doubles) one more time at some $L = L' + \Delta L$, the cluster previously largest becomes the second largest, $C_1 \rightarrow C_2$ (or disappears in the case of doubling). Thus it is guaranteed that during percolation two clusters of sizes $C_1 \geq N/3$ and $C_2 \geq N/3$ are generated, which necessarily join at some time $L > L'$. Therefore, in any such competitive process, prohibited growth $p_{gr} = 0$ implies that the largest gap is macroscopic,

$$\frac{\Delta C_{\max}}{N} \geq \frac{1}{3} \tag{4}$$

for all N . Hence, all competitive percolation processes with $p_{gr} = 0$ show strongly discontinuous transitions with a strong impact of single-link additions. As we show in the Supplementary Information, such a gap necessarily occurs at or beyond $\ell_c = 1$; thus, for extremal competition with $p_{gr} = 0$ the percolation point, where the largest cluster becomes macroscopic, does not necessarily coincide with the point where the largest gap occurs.

Single links induce gaps in large finite systems

Nevertheless, many weakly discontinuous transitions still exhibit essentially macroscopic gaps for large finite systems. We conjecture that competitive percolation processes in nature (or engineering or the social world), in particular spatially extended systems with limited-range interactions will naturally enable the largest cluster to grow, $p_{gr} > 0$ (as do all competitive percolation processes for non-global clique and edge competition), and they generically exhibit weakly discontinuous (if not continuous) percolation transitions^{31,32}. In specific limiting models analytic mean-field considerations yield

$$\frac{\Delta C_{\max}}{N} \sim N^{-\beta}, \beta > 0 \tag{5}$$

thus confirming (2). For instance, in a model variant where the largest cluster joins with the smallest available with probability p , and otherwise the two smallest clusters join with probability $1 - p$, we analytically find that (see Supplementary Information for a detailed derivation)

$$\beta = 1 + \frac{\log(2)}{\log[(1-p)/(2-p)]} \approx \frac{p}{2\log(2)} \tag{6}$$

for $0 \leq p \ll 1$ scales roughly linearly with p .

Notably, if largest-cluster growth does not occur, $p = 0$, we have $\beta = 0$ and $\Delta C_{\max}/N > 0$ in the thermodynamic limit, consistent with equation (4). More importantly, these results show that even when the largest cluster grows the slightest, that is, for arbitrarily small $p > 0$, the percolation transition is weakly discontinuous, because $\beta > 0$ as soon as $p \neq 0$. Direct numerical simulations agree well with our analytical prediction (6); see Fig. 4. The finding that $\beta > 0$ as soon as $p > 0$ is consistent with the above general result (compare with equation (2) and equation (5)) that for arbitrarily small probability $p_{gr} > 0$ of cluster growth the percolation transition is already weakly discontinuous, often with small positive exponents β and thus essentially macroscopic gaps in large finite systems (see numerical example below). More generally, the results above suggest that any process with non-maximal competition (including non-maximal edge competition ($m = 2$) showing ‘explosive percolation’^{17,19,20,33}) generically shows weakly discontinuous transitions.

Finite-size scaling and coexisting large clusters

Further extensive numerical scaling analysis reveals that the gaps in the generic competitive percolation processes we consider indeed occur coincident with the point where the largest cluster size is

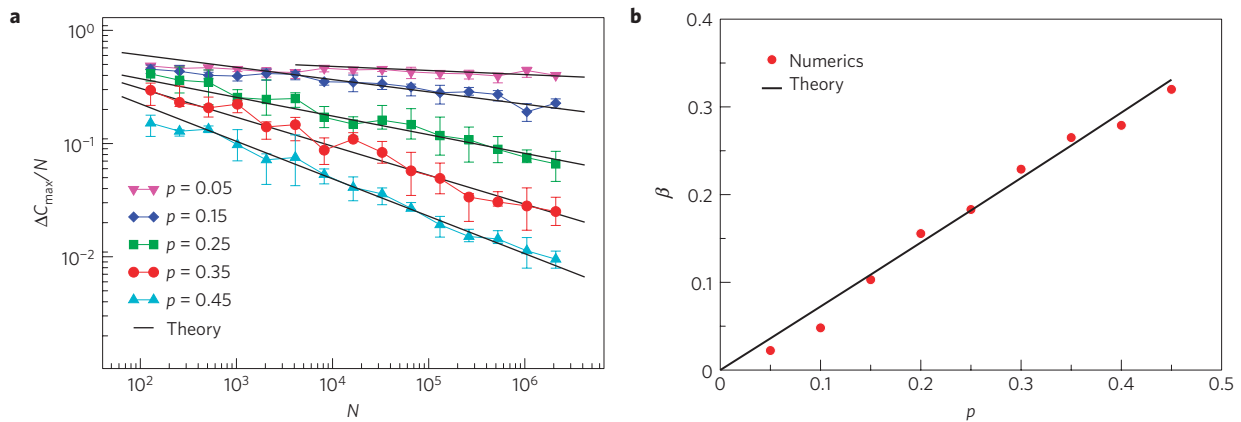


Figure 4 | Weakly discontinuous transition in stochastic mixture of largest-cluster growth (with probability p) and suppressed growth.

a, Double-logarithmic plot of $\Delta C_{\max}/N$ versus N for different p . The slopes of the theoretical mean-field prediction (black lines; ranging from $\beta = 0.036$ ($p = 0.05$) to $\beta = 0.33$ ($p = 0.45$)) asymptotically well fit the gap sizes obtained from numerical simulations (symbols). The symbols indicate averages over 10 realizations; error bars indicate best approximations to 25% quantiles and reflect system-intrinsic fluctuations. **b**, The theoretically derived exponent β (6) as a function of p (no fit parameter) systematically well predicts those found from fitting the data in **a** (red dots).

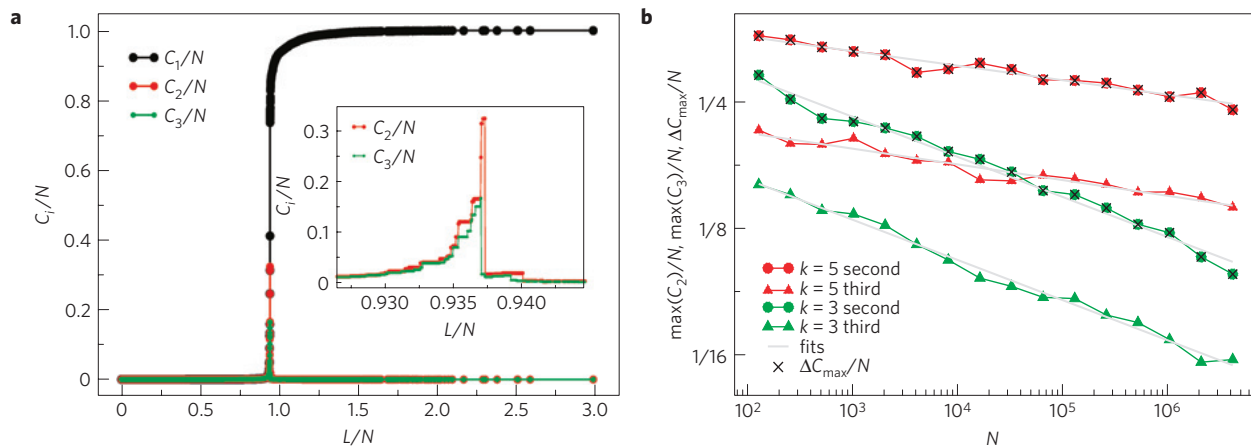


Figure 5 | Coexistence of several large clusters. **a**, Simultaneous emergence of the largest cluster of size C_1 , the second-largest cluster C_2 and the third-largest cluster C_3 in a competitive percolation process (clique percolation, $k = 4$, $N = 2^{15}$). Inset: blow-up of C_2 and C_3 in the region around the transition point. **b**, The maximal sizes of second- and third-largest clusters as a function of network size N indicate that they have the same order of magnitude and the same scaling, which is moreover identical to that of ΔC_{\max} . In particular, $\max_L C_i(L) \sim \Delta C_{\max} \sim N^{-\beta}$ for $i \in \{2, 3\}$ with $\beta = 0.095 \pm 0.003$ for $k = 3$ and $\beta = 0.036 \pm 0.002$ for $k = 5$. The maximum gap size ΔC_{\max} (crosses) is in fact equal to the maximum size of the second-largest cluster. Thus, there is no unique large cluster right at the transition even for very large finite systems.

discontinuous (Supplementary Fig. S2). Moreover, immediately before the transition, not only the largest gap size, but also the second-largest cluster, the third-largest cluster and so on, seem essentially macroscopic (Fig. 5). In particular, the size of the maximum second-largest cluster generically is exactly equal to the maximum gap size, $\Delta C_{\max} = \max_L C_2(L)$; see Supplementary Information for a derivation. Thus for small β the largest cluster is essentially non-unique, in contrast to standard continuous percolation transitions. This is consistent with refs 23,26, where cluster sizes and their ranks were studied qualitatively. Finally, analytical arguments (see Supplementary Information) also demonstrate that the percolation strength, defined as the difference in largest-cluster size immediately after and immediately before the gap^{20,25}, is exactly equal to the size of the second-largest cluster before the transition, which in turn scales with the same exponent β as the gap size (2). Further recent work also considers continuity properties of the transition regime³⁴ on the coarse scale but does not study the impact of single links. As shown above, single-link additions induce several new distinctive features of percolation transitions

and thus serve as key mechanisms controlling competitive percolation processes.

Interestingly, the so-called k -cores of the evolving graph, serving as the key example of the drastic impact of single links in traditional percolation theory^{35,36}, exhibit dynamics very similar to that for Erdős–Rényi percolation, even for extreme processes with $p_{gr} = 0$. The k -core of a graph is the largest subgraph with minimum degree at least k . As numerical simulations indicate (Supplementary Fig. S6), the size of the 2-core increases continuously from zero whereas k -cores for all $k \geq 3$ exhibit a discontinuous jump induced by single-link additions. These results hold for both Erdős–Rényi and competitive percolation processes. Even for extreme processes with $p_{gr} = 0$ the 2-core is still continuous, but with the location of the transition moved to larger values compared with the point of percolation. The dynamics of k -cores is thus very similar for competitive and standard, non-competitive percolation processes, in stark contrast to the dynamics of the largest-cluster size. This is true even though, as shown above, the latter is also strongly influenced by single-link additions.

Discussion

These results explain how increasing the level of competition strengthens the impact of single-link additions, thus controlling the type of transition. In particular, the exponent β tells us to what extent single-link additions change macroscopic connectivity. For generic competitive processes β is smaller than for non-competitive ones (see Fig. 3), but our numerical and analytic results indicate that they are still distinct from zero. Only processes with global competition or other extreme forms of competition yield $\beta = 0$ and thus a discontinuous gap ΔC_{\max} induced by single-link addition. Other, more generic processes typically exhibit $\beta > 0$ and thus a weakly discontinuous transition.

It is important to note that percolation processes with only moderate competition may already yield very small positive exponents and thus essentially macroscopic gaps (see Fig. 2). Here we use ‘essentially macroscopic’ to mean that the addition of single links in systems of physically large size induces gaps that are of relevant size (substantial fraction of system size) and that the gap sizes increase with stronger competition (for example increasing k), yielding a decreasing exponent $\beta \rightarrow 0$ as $k \rightarrow N$. As a consequence, even processes actually exhibiting weakly discontinuous transitions may show large gaps in systems of physically relevant size (compare with Fig. 3). For instance, if $\beta = 0.02$, a system of macroscopic, but finite size $N = 10^{23}$ exhibits a gap of $\Delta C_{\max}/N \sim N^{-\beta} \approx 0.35$, although formally $\Delta C_{\max}/N \rightarrow 0$ as $N \rightarrow \infty$. For many real processes with already moderate forms of competition, we expect exponents β close to zero, and thus conjecture that single links may have a strong impact on how such a network becomes connected.

In summary, our results demonstrate how, in competitive percolation, keeping the growth rate of the largest cluster small strengthens the impact of single-link additions that merge smaller clusters. Growing (i) and overtaking (ii) markedly distinguish the microscopic dynamics in systems exhibiting competitive percolation. The more largest-cluster growth is suppressed, the more relevant the discontinuous gap becomes in large systems of given finite size. Single-link additions may then induce an essentially macroscopic gap even for weakly discontinuous transitions if competition is sufficiently strong.

Our main results do not rely on the specific random network percolation process or the specific forms of competition considered and thus suggest that the phenomena described are largely independent of the underlying system. In particular, we expect that the addition of single links can also have a strong impact on lattices (compare refs 21,37), where so far only macroscopic observables have been studied and the impact of single links remains unknown.

Interestingly, a protein homology network has recently been identified¹⁰ showing macroscopic features akin to explosive percolation. Individual links may also induce abrupt changes in several other growing networked systems, possibly with severe consequences for the systems’ dynamics and function (compare refs 35,36,38). For instance, growing one or a few extra synaptic connections in a neuronal circuit may strongly alter the global connectivity and thus the overall activity of the circuit^{28,29,39}; specific infected individuals travelling to one but not another location may drastically change the patterns of infectious diseases¹¹; and the macroscopic properties of complex systems exhibiting competitive aggregation dynamics of physical or biological units may exhibit abrupt phase transitions induced by a small set of specific individual bonds newly established; compare, for example, refs 40,41. Our study thus not only provides recipes (by looking for certain competitive cluster formation) to identify real systems that could exhibit a (weakly) discontinuous percolation transition, but also shows that and how single-link additions in such systems may induce essentially macroscopic gaps, and in turn a collective, very abrupt change of structure and dynamics.

The current study answers how single-link dynamics underlies competitive percolation in general, but does not tell us how single-link additions are actually generated and controlled in any given real system. Future work must bridge this gap and establish how competitive percolation, and in particular the creation of essentially macroscopic jumps due to single-link additions, is influenced by predefined structure, for example for percolation processes on lattices and in geometrical or topological confinement occurring in nature^{10,19–21,23}.

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Author contributions

All authors conceived and designed the research, contributed analysis tools and analysed the data. J.N. carried out the numerical experiments. All authors worked out the theory and wrote the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturephysics. Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions>. Correspondence and requests for materials should be addressed to J.N.