Explosive site percolation with a product rule

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We study the site percolation under Achlioptas process (AP) with a product rule in a 2 – dimensional (2D) square lattice. From the measurement of the cluster size distribution, $P_s$, we find that $P_s$ has a very robust power-law regime followed by a stable hump near the transition threshold. Based on the careful analysis on the $P_s$ distribution, we show that the transition should be discontinuous. The existence of the hysteresis loop in order parameter also verifies that the transition is discontinuous in 2D. Moreover we also show that the transition nature from the product rule is not the same as that from a sum rule in 2D.

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The percolation transition describing the emergence of large-scale connectivity in lattice systems or complex networks has been extensively studied in statistical mechanics and related fields due to its possible applications to various phenomena such as sol-gel transition and polymerization, resistor networks, and epidemic spreading [1]. When the occupation probability of node (site) is lower than certain threshold $p_c$, all the clusters are microscopic. As the occupation probability increases, the macroscopically connected cluster emerges. Such transition in the ordinary percolation is a continuous transition [1].

On the other hand, there have been several attempts to find a percolation model which undergoes a discontinuous transition. The discontinuous percolation transition can be found in the modelling of magnetic systems with significant competition between exchange and crystal-field interactions [2, 3]. The similar phenomena has been found in financial systems [4], in which two equally probable phases exit. Other examples of the discontinuous transition in percolation are the formation of infinite cluster under a central-force [4] and the cascade of failure in interdependent networks [6].

Recently, Achlioptas et al. [5] suggested a simple process in which the growth of large clusters is systematically suppressed and the process is usually called as Achlioptas process (AP). Based on the analysis of transition interval it was argued that the percolation transition under AP is explosive and discontinuous. Several variant of models have been investigated to understand the general properties and conditions which cause such non-trivial discontinuous transition [8, 11]. Some examples of such non-trivial transition has been found in nano-tube based system [11], protein homology network [12], and community formation [13].

However, more recent studies on the percolation transition under AP reveals several evidences which strongly suggest that the transition can be continuous. For example, da Costa et al. [14] argued that the transition in the complete graph (CP) is continuous, even though the order parameter exponent is very small ($\beta \simeq 0.056$). From the measurement of the cluster size distribution Lee et al. [13] also argued that the transition in CP is continuous. Grassberger et al. [16] also argued that the transition, even in the low-dimensional systems, can be continuous based on a measurement of the order parameter distribution.

Since most of the studies on the criticality of AP process are restricted to the infinite dimensional systems, it is still not clear whether AP also produces a continuous transition in lower dimensional systems or not. For example, in the bond percolation under AP in a 2-dimensional (2D) square lattice, the product rule was argued to produces a discontinuous transition based on a finite-size scaling [8, 17]. In contrast Grassberger et al. [16] argued that transition of the 2D AP bond percolation is still continuous. We therefore cannot exclude the possibility that the transition nature of the AP in the mean-field limit can be different from that in lower-dimensional systems, like the Potts model [18]. Moreover, based on the measurement of hysteresis [19], a sum rule for the 2D site percolation possibly makes the transition continuous in the thermodynamic limit. This indicates that under the AP-like processes the bond percolation and site percolation may have different transition natures in the 2D lattice. In the ordinary percolation, bond and site percolations are known to belong to the same universality class [1]. In contrast, the results in Refs. [8, 17, 19] show the possibility that under AP the bond percolation with a product rule and the site percolation with a sum rule do not belong to the same universality class. Therefore, it is theoretically important and interesting to investigate whether in a low-dimensional system the product rule and the sum rule belong to the same universality class or not. In order to achieve this purpose, we investigate the site percolation under AP with a product rule and show that AP with the product rule produces a clear discontinuous transition in a 2D lattice. For this we carefully analyze the cluster size distribution and hysteresis.

AP in 2D site percolation is defined as follows: (I) We select two sites $\alpha$ and $\beta$ at random. (II) Let $\{s_{\alpha_1}, s_{\alpha_2}, \cdots, s_{\alpha_n}\}$ be the sizes of clusters which form into a new big cluster with the size
\[ \sum_{k=1}^{\nu} s_{\alpha k} + 1 \left( \sum_{k=1}^{m} s_{\beta k} + 1 \right) \] by occupying the site \( \alpha (\beta) \). Here the cluster size is defined by the number of sites in the cluster. Then calculate the products

\[ \pi_{\alpha} = \prod_{i=1}^{n} s_{\alpha i} \quad \text{and} \quad \pi_{\beta} = \prod_{j=1}^{m} s_{\beta j}. \tag{1} \]

This rule is generally called product rule (PR). (II) If \( \pi_{\alpha} \leq \pi_{\beta} \) (\( \pi_{\alpha} \geq \pi_{\beta} \)) then site \( \beta \) (\( \alpha \)) remains to be vacant. The processes (II) and (III) prefer the connection between small clusters, which causes the cluster repulsion or suppress the growth of large cluster. If the product in Eq. (1) is replaced by summation, then the rule is called as a sum rule. Recent study for site percolation with sum rule shows that the transition is continuous when the linear size of the lattice, \( L \), goes to infinity \( [19] \). Since we use a 2D square lattice \( n(m) \) in Eq. (1) is at most 4.

\[ P_s = \frac{n}{\sum_{i=1}^{n} s_{\alpha_i}} \]

![FIG. 1. (color online) (a) Plot of \( P_s \) for \( p = 0.75 \) or \( p < p_c \). The data for \( L = 1024 \) are denoted by black squares and those for \( L = 2048 \) are denoted by red circles. (b) Plot of \( P_s \) for \( p = 0.8 \) or \( p > p_c \). The solid line represents the relation \( P_s \sim s^{-\delta} \) with \( \delta \approx 0.90(2) \). The data points marked by “x” represents the \( P_s \) for macroscopically large clusters or the largest cluster. (c) The same plot for \( p = 0.77 \) or near the transition threshold. (d) Plot of \( P_s \) for \( p = 0.765 \) and \( p = 0.770 \) on the lattice with \( L = 2048 \).](image)

To understand the percolation transition physically to a deeper level, the properties of the cluster size distribution should be the first one to understand \([1] [12] [20]\). The cluster size distribution \( P_s(p) \) at a site occupation probability \( p \) is normally defined by the probability that a randomly selected site belongs to a cluster which has \( s \) sites (\( s \)-cluster). For ordinary percolation, it is well known that \( P_s(p_c) \) satisfies a power-law relation \([1]\),

\[ P_s(p_c) \sim s^{-\delta}, \tag{2} \]

with \( \delta \approx 1.05 \) at the percolation transition probability \( p_c \). Since, as we shall show, the percolation properties under AP depend on the history how the clusters are grown, we measure \( P_s(p) \) by filling sites from the vacant lattice or increasing \( p \). In Fig. (1) \( P_s(p) \)’s for 2D site percolation under AP with product rule (2DSAP) are displayed. \( P_s \) in Fig. (1) shows an anomalously unique behavior compared to that of the ordinary percolation (OP) \([1]\) and that of the AP percolation on the complete graph (APCG), which was argued to undergo the continuous phase transition \([12]\).

When \( p < p_c \), \( P_s \) for 2DSAP has a hump in the tail as \( p \) approaches to \( p_c \), \( [20] \). In this regime, \( P_s \) does not depend on \( L \) or \( N = L \times L \) as shown in Fig. (1a). In OP, \( P_s \) normally decays exponentially as \( s \) gets larger in this regime. For the detailed comparison to those of OP and APCG, let’s call \( s \) at which the hump is maximal \( s_H \). In OP we cannot identify \( s_H \). In APCG \( s_H \) and \( P(s_H) \) was argued to satisfy the scaling behavior, \( s_H \approx N^x \) and \( P(s_H) \approx N^{-y} \) with \( x > 0 \) and \( y > 0 \) \([13]\).

Therefore in APCG the hump has the negligible contribution and \( P_s \) satisfies the same scaling form as Eq. (2) in the limit \( N \to \infty \). This \( P_s \) behavior in APCG is believed to be one of the signals for the continuous transition as in OP. In contrast \( s_H \) and \( P(s_H) \) of 2DSAP do not depend on \( L \) or \( s_H \approx \text{const} \) and \( P(s_H) \approx \text{const} \) as \( L(N) \) gets larger. We have numerically checked this behavior for \( N = 2^{18}, 2^{18}, 2^{20}, 2^{22} \). This behavior for 2DSAP means that there should be many considerably large macroscopic \( s \)-clusters with \( s \approx s_H \) before transition, which indicates the unstable or sudden appearance of the macroscopic cluster by connecting these clusters when \( p \) increases.

Even when \( p > p_c \), \( P_s \) for 2DSAP has a unique behavior as shown in Fig. (1b). Except \( P_s \) for the macroscopically large cluster, \( P_s \) for macroscopically finite clusters for \( p > p_c \) still satisfies the same power-law \( P_s = A s^{-\delta} \) with the same exponent \( \delta \) as \( P_s(p_c) \) or \( \delta = 0.90(3) \), which we will explain with the data in Fig. (1c). The difference between \( P_s(p > p_c) \) and \( P_s(p_c) \) is in \( A \) and the tail part for finite clusters. As \( p \) becomes larger than \( p_c \), \( A \) decreases and the length of tail becomes shorter compared to \( P_s \) at \( p_c \). The power-law behavior is very robust, because it maintains for nearly four decades or \( 10^3 - 10^5 \) as shown in Fig. (1b) before appearing finite-size effects. Moreover, the power-law behavior for \( p > p_c \) is nearly independent of \( L \) as for \( p < p_c \) (see Fig. (1b)). This power-law behavior for the finite clusters has been confirmed even for large \( p \) up to \( p = 0.9 \). In contrast \( P_s \) for microscopic clusters for \( p > p_c \) in OP and APCG exponentially decays. In 2DSAP the product rule makes the macroscopic cluster absorb relatively smaller clusters when \( p \) gets large in the regime \( p > p_c \). Therefore the larger microscopic clusters cannot easily disappear. The sustainability of such metastable clusters seems to be the origin of the power-law of \( P_s \) for \( p > p_c \). As we shall see the hysteresis of 2DSAP is consistent with the power-law for \( p > p_c \) because of such metastable states.

The phase transition for 2DSAP naturally occurs at \( p \) which divides the two regimes of \( P_s \) described by Fig.
The transition threshold $p_c$ for 2DSAP is estimated by the data in Fig. 1(c) and Fig. 1(d). As shown in Fig. 1(c) and in Fig. 1(d) at $p = 0.770$ $P_s$ for the macroscopically large cluster starts to be detached from the continuous distribution of $P_s$ for microscopic clusters. This detachment behavior seems to be independent of $L(N)$ as shown in Fig. 1(c).

As shown in Fig. 1(d), this detachment behavior barly occurs and the hump-like tail still exists for $p = 0.765$. We have scrutinized $P_s$ between $0.765 < p < 0.770$, but the sharp discrimination between the hump-like behavior and the detachment cannot be made. Such complex behavior mixing the hump and $P_s$ for the macroscopically large clusters for $p \approx p_c$ seems to be a unique behavior of 2DSAP. Therefore the best estimation of $p_c$ from the numerical data of $P_s$ is $p_c = 0.768(3)$. At $p \approx p_c$, $P_s$ satisfies the power-law $P_s = A s^{-\delta}$ with $\delta = 0.90(2)$ very well except for the very tiny tail part. Again this power-law $P_s = A s^{-0.9}$ is very robust and holds for more than four decades. The result $\delta = 0.9$ also provides a very important clue to understand the transition nature of 2DSAP.

Since $P_s$ is a probability, $P_s$ should satisfy the normalization condition, $\sum_s P_s = p$. However, the summation $\sum_s P_s$ diverges if $\delta < 1$. Therefore, there should be a cutoff $s_c$ in the upper limit as $\sum_s^c P(s) = p$. In the limit $N \to \infty$, $s_c/N \to 0$. Thus, there should be a discontinuous jump to produce a macroscopic cluster in the limit $N \to \infty$ and the transition becomes discontinuous.

The physical origin of the discontinuous transition should come from the merge of $s$-clusters with $s \approx s_h$ to form the macroscopic cluster when $p$ gets larger to be $p = p_c$.

One of the most generally accepted and the simplest methods to verify whether the observed transition is discontinuous or not is the measurement of the hysteresis. The hysteresis measurement for the explosive percolation has also been emphasized in Refs. [11, 19]. The hysteresis is a history-dependent property of a system and usually observed in the discontinuous phase transition because of the metastable state. If the transition is discontinuous, then the route of changes in the order parameter $P_{LC}$ during the process of filling sites from the vacant lattice or increasing $p$ would be different from that for the process of deleting sites from the fully-occupied lattice or decreasing $p$. The order parameter, $P_{LC}$, is defined by the probability that a site belongs to the largest cluster

$$ P_{LC} = \frac{N_{LC}}{N}. \quad (3) $$

Here, $N_{LC}$ is the number of sites in the largest cluster.

In Fig. 2(a), to check the existence of hysteresis we compare the measured $P_{LC}$’s along the process of increasing $p$ (solid lines) and along the process of decreasing $p$ from $N = 2^{12}$ to $N = 2^{20}$. For the decreasing process, we slightly modify the rule (III) to easily break the larger clusters into smaller ones [11], since the rules (II) and (III) suppress the formation of a large cluster; i.e., if $\pi_a \geq \pi_b$ then we delete the site $\alpha$. With this modified rule we find that there exists a hysteresis for various $L$ as shown in Fig. 2(a).

Now the remaining question is whether the hysteresis robustly remains in the $L \to \infty$ limit. For the systematic analysis, we show the dependence of area, $A(L)$, enclosed by $P_{LC}(L)$ for the increasing and decreasing processes on $L$. If the system undergoes a continuous transition, then $A(L)$ should vanish in the limit $L \to \infty$. However, our data clearly shows that $A(L)$ increases as $L$ increases or, at least, seems to saturate to a nonzero value unlike the sum rule [13] in which $A(L) \to 0$ as $L \to \infty$. This shows that 2DSAP undergoes a discontinuous transition. And in 2D lattice, the product rule makes a completely different transition nature from that of the sum rule [10].

This hysteretic property of 2DSAP should be from the sustainability of the metastably larger clusters, which is consistent with the analysis of $P_s$ in Fig. 1.

Since we don’t know the physically corresponding formula to Hamiltonian or free energy for 2DSAP and there exists the nontrivial hysteretic property, it might be physically nonsense to discuss about the finite-size scaling. However for the comparison’s purpose to other works on explosive percolation [8,10], we now present the finite size analysis around $p_c = 0.768(3)$, which is the percolation transition probability for the $p$-increasing process. From the data in Fig. 2(a), $P_{LC}(L)$ at the $p_c$ is estimated.
as shown in Fig. 3(a). $P_{LC}(L)$ seems to satisfy the relation $P(L) \sim L^{-B}$ with $B = 0.011(2)$, where conventionally $B$ corresponds to $\beta/\nu$. This value of $B$ is very close to zero. Thus, in the inset of Fig. 3(a), we also fit the data to the relation $P(L) \sim -\log L$ which corresponds to the case $B \to 0$. Since we cannot exclude the possibility $B = 0$ or $\beta = 0$, the possibility for $P_{LC}(L \to \infty)$ at $p_c$ to have discontinuous jump cannot be excluded. We also measure the mean cluster size, defined by

$$S(p, L) = \frac{\sum_s sP_s}{\sum_s P_s}, \quad (4)$$

$\sum_s$ represents the summation over all $s$ except the largest one. $S(p, L)$’s maximal value, $S_{max}(L)$, is displayed in Fig. 3(b). Again we fit the data to the conventional scaling relation $S_{max}(L) \sim L^{-C}$, and we obtain $C = 1.98(1)$, where $C$ corresponds to conventional $\gamma/\nu$.

![Figure 3](image)

**FIG. 3.** (a) Plot of $P_{LC}(L)$ measured at $p_c$ against $L$. The solid line represents the relation $P(L) \sim L^{-B}$ with $B = 0.012$. Inset: Plot of $P_{LC}(L)$ in semi-log scale. The solid line represents the relation $P(L) \sim -\log L$. (b) Plot of $S_{max}(L)$ against $L$. The solid line denotes $S_{max} \sim L^C$ with $C = 1.98$.

In summary, we study the site percolation under AP with a product rule in a 2D lattice. From the measurement of $P_s(p)$, we find that the $P_s(p)$ have a very stable hump when $p < p_c$. This indicates that below $p_c$ large number of stable $s$-clusters with $s \simeq s_H$ exist but their sizes are still microscopic. As $p$ approaches to $p_c$, $P_s(p)$ has a very robust power-law regime followed by the hump. Since the obtained value of the exponent, $\delta$, for the power-law regime in the vicinity of $p_c$ is less than unity, there should be a cutoff $s_c$ in the possible cluster size for $p \simeq p_c$, unlike OP [1]. Thus, to generate a macroscopic cluster there should be a discontinuous jump in the limit $L \to \infty$ and the transition becomes discontinuous. The non-vanishing hysteresis in $P_{LC}$ also verifies that the transition is discontinuous. This result clearly shows that the percolation transition caused by the product rule in a 2D square lattice is discontinuous.

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