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EXPLICIT ISOPERIMETRIC CONSTANTS AND PHASE TRANSITIONS IN THE RANDOM-CLUSTER MODEL

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The random-cluster model is a dependent percolation model that has applications in the study of Ising and Potts models. In this paper, several new results are obtained for the random-cluster model on nonamenable graphs with cluster parameter $q \geq 1$. Among these, the main ones are the absence of percolation for the free random-cluster measure at the critical value and examples of planar regular graphs with regular dual where $p_c^{\text{free}}(q) > p_u^{\text{wired}}(q)$ for q large enough. The latter follows from considerations of isoperimetric constants, and we give the first nontrivial explicit calculations of such constants. Such considerations are also used to prove nonrobust phase transition for the Potts model on nonamenable regular graphs.

1. Introduction. One of the most important and much-studied dependent percolation models today is the random-cluster model. It was introduced in 1972 by Fortuin and Kasteleyn [19], and after a decade and a half of relative silence, the model was revived in the late 1980s with the influential papers by Swendsen and Wang [43], Edwards and Sokal [15] and Aizenman, Chayes, Chayes and Newman [1]. Since then, the random-cluster model has served as a major tool in studying Ising and Potts models, and has also been studied in its own right by several authors. This paper is an investigation of various aspects of the random-cluster model on so-called nonamenable graphs, and we shall obtain results that are intrinsic to the model itself, as well as some applications to the Potts model. Our main results, in order of importance, are the following:

1. We consider *four* (possibly different) *critical values* for the random-cluster model on a given Cayley graph, and we sort out how these can relate to each other (Sections 3 and 4). In particular, we show that on all nonamenable planar regular graphs with regular dual one has for q large enough that $p_c^{\text{free}}(q) > p_u^{\text{wired}}(q)$. For this purpose, we give the first explicit nontrivial calculations of positive *isoperimetric constants*.
2. We show *lack of percolation* for the free random-cluster measure at the lower critical value on all nonamenable quasi-transitive unimodular graphs (Theorem 3.1), thereby extending a result of [6] and [7] for i.i.d. percolation.

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3. The random-cluster model is exploited to show that the Potts model on all nonamenable regular graphs exhibits, for entire intervals of temperatures, phase transition but not so-called *robust phase transition* (Section 5).

We also present a number of other results about the random-cluster measures and about their relationships to Potts models.

We shall begin by recalling in Section 2 some basics concerning random-cluster and Potts models. In Section 3 we discuss the lack of percolation at criticality. Proceeding to our results on the inequalities between the four critical values p_c^{wired}, p_c^{free}, p_u^{wired} and p_u^{free}, we shall find that most of them are fairly immediate. An exception is the result that $p_c^{\text{free}}(q) > p_u^{\text{wired}}(q)$ can occur for some graphs and some q, which requires careful analysis (carried out in Section 4) of the random-cluster model on regular tilings of the hyperbolic plane. Parts of this analysis are based on the Peierls-type comparison methods of Jonasson and Steif [32] and Jonasson [31], and these methods are also exploited in Section 5 to obtain our result on nonrobust phase transition for the Potts model.

Since isoperimetric constants are of independent interest, we state here our result concerning them. A regular Euclidean polygon of $d^\dagger$ sides has interior angles $\pi(1 - 2/d^\dagger)$. In order for such polygons to form a tessellation of the plane with d polygons meeting at each vertex, we must have $\pi(1 - 2/d^\dagger) = 2\pi/d$, that is, $1/d + 1/d^\dagger = 1/2$ or, equivalently, $(d-2)(d^\dagger - 2) = 4$. In all three such cases, tessellations have been well known since antiquity. In the hyperbolic plane, the interior angles can take any value in $(0, \pi(1 - 2/d^\dagger))$, whence a tessellation exists only if $1/d + 1/d^\dagger < 1/2$ or, equivalently, $(d-2)(d^\dagger - 2) > 4$; again, this condition is also sufficient for the existence of a hyperbolic tessellation, as has been known since the 19th century. [We note that the cases $(d-2)(d^\dagger - 2) < 4$ correspond to the spherical tessellations that arise from the five regular solids.]

Let $G = (V, E)$ be the planar graph formed by the edges and vertices of one of these regular tessellations by polygons with $d^\dagger$ sides and with degree d at each vertex. Given a finite set $K \subset V$, write $\partial_E K$ for the set of edges with exactly one endpoint in K. We prove in Theorem 4.1 that

$$\inf\left\{\frac{|\partial_E K|}{|K|}; K \subset V \text{ finite and nonempty}\right\} = (d-2)\sqrt{1 - \frac{4}{(d-2)(d^\dagger - 2)}}.$$

This should be compared to the regular tree of degree d, where the left-hand side is equal to $d - 2$. This formula also makes easy the task of deciding whether such a graph satisfies one of the conditions of high nonamenability that appear in [41]; such a condition has numerous implications for various models on the graph. Series and Sinaĭ [42] were the first to consider the Ising model on graphs of hyperbolic tessellations.

2. Background. In the following subsections, we recall some preliminaries on random-cluster and Potts models and on stochastic domination and various classes of infinite graph structures. General references for Sections 2.1–2.4 are

Häggström [29] and Georgii, Häggström and Maes [22], whereas, for Section 2.5, we refer to Benjamini, Lyons, Peres and Schramm [6].

2.1. *Random-cluster and Potts models on finite graphs.* Let $G = (V, E) = (V(G), E(G))$ be a finite graph. An edge $e \in E$ connecting two vertices $x, y \in V$ is also denoted $[x, y]$. An element ξ of $\{0, 1\}^E$ will be identified with the subgraph of G that has vertex set V and edge set $\{e \in E; \xi(e) = 1\}$. An edge e with $\xi(e) = 1$ [$\xi(e) = 0$] is said to be open (closed). Of central importance to us will be the number of connected components of ξ, which will be denoted $\|\xi\|$. We emphasize that in the definition of $\|\xi\|$ isolated vertices in ξ also count as connected components.

The *random-cluster measure* $\mathsf{RC} := \mathsf{RC}^G_{p,q}$ (sub- and superscripts will be dropped whenever possible) with parameters $p \in [0, 1]$ and $q > 0$ is the probability measure on $\{0, 1\}^E$ that to each $\xi \in \{0, 1\}^E$ assigns probability

$$\mathsf{RC}(\xi) := \frac{q^{\|\xi\|}}{Z} \prod_{e \in E} p^{\xi(e)} (1 - p)^{1-\xi(e)}, \tag{1}$$

where $Z := Z^G_{p,q} := \sum_{\xi \in \{0,1\}^E} q^{\|\xi\|} \prod_{e \in E} p^{\xi(e)} (1 - p)^{1-\xi(e)}$ is a normalizing constant. It is easy to see that if X is a $\{0, 1\}^E$-valued random variable with distribution RC, then we have, for each $e = [x, y] \in E$ and each $\xi \in \{0, 1\}^{E \setminus \{e\}}$,

$$\mathsf{RC}\big(X(e) = 1 \,\big|\, X(E \setminus \{e\}) = \xi\big) = \begin{cases} p, & \text{if } x \leftrightarrow y, \\ \dfrac{p}{p + (1 - p)q}, & \text{otherwise}, \end{cases} \tag{2}$$

where $x \leftrightarrow y$ is the event that there is an open path (i.e., a path of open edges) from x to y in $X(E \setminus \{e\})$. Here, $X(E')$ denotes the restriction of X to E' for $E' \subseteq E$.

When $q = 1$, we see that all edges are independently open and closed with respective probabilities p and $1 - p$, so that we get the usual i.i.d. bond percolation model on G, which we refer to as *Bernoulli*(p) percolation. All other choices of q yield dependence between the edges. Throughout the paper, *we shall assume that* $q \geq 1$. This conforms with most other studies of the random-cluster model, and there are two reasons for doing this. First, when $q \geq 1$, the conditional probability in (2) becomes increasing not only in p but also in ξ, and this allows a set of very powerful stochastic domination arguments that are not available for $q < 1$. Second, it is only random-cluster measures with $q \in \{2, 3, \ldots\}$ that have proved to be useful to the analysis of Potts models, which we now describe.

Given the finite graph G and an integer $q \geq 2$, the q-state Potts model provides a model for picking an element $\omega \in \{1, \ldots, q\}^V$ in a random but correlated way. The values $1, \ldots, q$ attainable at each vertex $x \in V$ are called *spins*. Fix the so-called *inverse-temperature* parameter $\beta \geq 0$ and define the *Gibbs measure for the* q*-state*

Potts model on G at inverse temperature β, denoted $\mathsf{Pt} := \mathsf{Pt}^G_{q,\beta}$, as the probability measure that to each $\omega \in \{1, \dots, q\}^V$ assigns probability

$$\mathsf{Pt}(\omega) := \frac{1}{Z} \exp\left(-2\beta \sum_{[x,y]\in E} \mathbf{1}_{\{\omega(x)\neq\omega(y)\}}\right),$$

where Z is another normalizing constant [different from the one in (1)]. The main link between random-cluster and Potts models is the following well-known result.

PROPOSITION 2.1. *Fix the finite graph G, an integer $q \geq 2$ and $p \in [0, 1]$ Pick a random edge configuration $X \in \{0, 1\}^E$ according to the random-cluster measure $\mathsf{RC}^G_{p,q}$. Then, for each connected component $\mathcal{C}$ of X, pick a spin uniformly from $\{1, \dots, q\}$ and assign this spin to all vertices of $\mathcal{C}$. Do this independently for different connected components. The $\{1, \dots, q\}^V$-valued random spin configuration arising from this procedure is then distributed according to the Gibbs measure $\mathsf{Pt}^G_{q,\beta}$ for the q-state Potts model on G at inverse temperature $\beta := -\frac{1}{2}\log(1 - p)$.*

This provides a way of reformulating problems about pairwise dependencies in the Potts model into problems about connectivity probabilities in the random-cluster model. Aizenman, Chayes, Chayes and Newman [1] exploited such ideas to obtain results about the phase transition behavior of the Potts model. See [29] for a list of references of other applications of the random-cluster model to the Potts model.

2.2. *Stochastic domination and weak convergence.* Let E be any finite or countably infinite set. (The reason for denoting it by E is that, in our applications, it will be an edge set.) For two configurations $\xi, \xi' \in \{0, 1\}^E$, we write $\xi \preccurlyeq \xi'$ if $\xi(e) \leq \xi'(e)$ for all $e \in E$. A function $f : \{0, 1\}^E \to \mathbf{R}$ is said to be *increasing* if $f(\xi) \leq f(\eta)$ whenever $\xi \preccurlyeq \eta$. For two probability measures μ and μ' on $\{0, 1\}^E$, we say that μ is *stochastically dominated* by μ', writing $\mu \overset{\mathcal{D}}{\preccurlyeq} \mu'$, if

$$\int_{\{0,1\}^E} f\, d\mu \leq \int_{\{0,1\}^E} f\, d\mu' \tag{3}$$

for all bounded increasing f. By Strassen's theorem, this is equivalent to the existence of a coupling $\mathbf{P}$ of two $\{0, 1\}^E$-valued random variables X and X', with respective distributions μ and μ', such that $\mathbf{P}(X \preccurlyeq X') = 1$.

A useful tool for establishing stochastic domination is Holley's inequality (see [29] or [22]). Since the conditional distribution in (2) is increasing both in ξ and in p (recall that we consider random-cluster measures only with $q \geq 1$), Holley's inequality applies to show that, for any finite graph $G = (V, E)$,

$$\mathsf{RC}^G_{p_1,q} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{RC}^G_{p_2,q},$$

whenever $p_1 \le p_2$. Similarly, we get, for conditional distributions, that

$$\mathsf{RC}^G_{p,q}\big(X \in \cdot \,\big|\, X(E') = \xi\big) \overset{\mathcal{D}}{\preccurlyeq} \mathsf{RC}^G_{p,q}\big(X \in \cdot \,\big|\, X(E') = \xi'\big), \tag{4}$$

whenever $E' \subseteq E$ and $\xi \preccurlyeq \xi'$.

We shall also be considering weak convergence of probability measures on $\{0,1\}^E$. For such probability measures $\mu_1, \mu_2, \dots$ and μ, we say that μ is the (weak) limit of μ_i as $i \to \infty$ if $\lim_{i\to\infty} \mu_i(A) = \mu(A)$ for all cylinder events A.

2.3. *The random-cluster model on infinite graphs.* Let $G = (V, E)$ be an infinite, locally finite graph. The definition (1) of random-cluster measures does not work in this case, because there are uncountably many different configurations $\xi \in \{0,1\}^E$. Instead, there are two other approaches to defining random-cluster measures on infinite graphs: one via limiting procedures and one via local specifications (Dobrushin–Lanford–Ruelle, or DLR, equations). We shall sketch the first approach and then explain how it relates to the second.

Let $V_1, V_2, \dots$ be a sequence of finite vertex sets increasing to V in the sense that $V_1 \subset V_2 \subset \cdots$ and $\bigcup_{i=1}^{\infty} V_i = V$. For any finite $K \subseteq V$, define

$$E(K) := \big\{[x,y] \in E; x, y \in K\big\},$$

set $E_i := E(V_i)$ and note that $E_1, E_2, \dots$ increases to E in the same sense that $V_1, V_2, \dots$ increases to V. Set ∂V_i to be the (inner) boundary of V_i, that is,

$$\partial V_i := \big\{v \in V_i; \exists\, [x,y] \in E \setminus E_i \text{ with } x = v\big\}.$$

Also set $G_i := (V_i, E_i)$ and let $\mathsf{FRC}^{G,i}_{p,q}$ be the probability measure on $\{0,1\}^E$ corresponding to picking $X \in \{0,1\}^E$ by letting $X(E_i)$ have distribution $\mathsf{RC}^{G_i}_{p,q}$ and setting $X(e) := 0$ for all $e \in E \setminus E_i$. Since the projection of $\mathsf{FRC}^{G,i}_{p,q}$ on $\{0,1\}^{E\setminus E_i}$ is deterministic, we can also view $\mathsf{FRC}^{G,i}_{p,q}$ as a measure on $\{0,1\}^{E_i}$, in which case it coincides with $\mathsf{RC}^{G_i}_{p,q}$. By applying (4) to the graph G_i with $E' := E_i \setminus E_{i-1}$ and $\xi \equiv 0$, we get that

$$\mathsf{FRC}^{G,i-1}_{p,q} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{FRC}^{G,i}_{p,q},$$

so that

$$\mathsf{FRC}^{G,1}_{p,q} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{FRC}^{G,2}_{p,q} \overset{\mathcal{D}}{\preccurlyeq} \cdots. \tag{5}$$

This implies the existence of a limiting probability measure $\mathsf{FRC}^G_{p,q}$ on $\{0,1\}^E$. This limit is independent of the choice of $\{V_i\}_{i=1}^{\infty}$, and we call it the random-cluster measure on G with *free boundary condition* (hence the F in FRC) and parameters p and q.

Next, define $\mathsf{WRC}^{G,i}_{p,q}$ as the probability measure on $\{0,1\}^E$ corresponding to first setting $X(E \setminus E_i) \equiv 1$ and then picking $X(E)$ in such a way that

$$\mathsf{WRC}^{G,i}_{p,q}\big(X(E_i) = \xi\big) = \frac{q^{\|\xi\|^*}}{Z} \prod_{e \in E_i} p^{\xi(e)}(1-p)^{1-\xi(e)},$$

where $\|\xi\|^*$ is the number of connected components of ξ *that do not intersect* ∂V_i. Similarly as in (5), we get

$$\mathsf{WRC}^{G,1}_{p,q} \overset{\mathcal{D}}{\succcurlyeq} \mathsf{WRC}^{G,2}_{p,q} \overset{\mathcal{D}}{\succcurlyeq} \cdots$$

(note the reverse inequalities) and thus also a limiting measure $\mathsf{WRC}^{G}_{p,q}$ which we call the random-cluster measure on G with *wired boundary condition* and parameters p and q.

We now briefly discuss how the above relates to the DLR approach to the random-cluster model on infinite graphs. It is natural to expect that the limiting measures $\mathsf{FRC}^{G}_{p,q}$ and $\mathsf{WRC}^{G}_{p,q}$ should satisfy some analogue of (2). Indeed, $\mathsf{FRC}^{G}_{p,q}$ admits conditional probabilities satisfying

$$\mathsf{FRC}^{G}_{p,q}\big(X(e) = 1 \,\big|\, X(E \setminus \{e\}) = \xi\big) = \begin{cases} p, & \text{if } x \leftrightarrow y, \\ \dfrac{p}{p + (1-p)q}, & \text{otherwise,} \end{cases} \tag{6}$$

for any $e \in E$ and any $\xi \in \{0,1\}^{E \setminus \{e\}}$, where the event $x \leftrightarrow y$ is defined as in (2). Although $\mathsf{WRC}^{G}_{p,q}$ does *not*, in general, satisfy the same local specification, it satisfies

$$\mathsf{WRC}^{G}_{p,q}\big(X(e) = 1 \,\big|\, X(E \setminus \{e\}) = \xi\big) = \begin{cases} p, & \text{if } x \overset{\infty}{\longleftrightarrow} y, \\ \dfrac{p}{p + (1-p)q}, & \text{otherwise,} \end{cases} \tag{7}$$

where $x \overset{\infty}{\longleftrightarrow} y$ denotes the event that either ξ contains a path from x to y or it contains an infinite self-avoiding path starting at x and an infinite self-avoiding path starting at y. In other words, $x \overset{\infty}{\longleftrightarrow} y$ is the same event as $x \leftrightarrow y$, except that in $x \overset{\infty}{\longleftrightarrow} y$ the path from x to y is allowed to go "via infinity." We think of this as a kind of compactification of the graph. These facts are stated in [22], Theorem 6.17. [That $\mathsf{FRC}^{G}_{p,q}$ satisfies (6) is due to [10]. The fact that $\mathsf{WRC}^{G}_{p,q}$ satisfies (7) can be proved analogously. Other proofs of (7) can be found in [22] and [31].] We call a probability measure on $\{0,1\}^E$ a *DLR random-cluster measure* (resp., a *DLR wired random-cluster measure*) with the given parameters p and q if it satisfies the local specifications in (6) [resp., in (7)]. (These local specifications are usually given on any finite edge set, rather than on a single edge. However, single-edge specifications are enough; see, e.g., [22], Theorem 6.18.) It turns out that $\mathsf{FRC}^{G}_{p,q}$ and $\mathsf{WRC}^{G}_{p,q}$ play the following special role in the class of DLR random-cluster and wired random-cluster measures: If μ is any DLR random-cluster measure or DLR wired random-cluster measure for G with parameters p and q, then

$$\mathsf{FRC}^G_{p,q} \overset{\mathcal{D}}{\preccurlyeq} \mu \overset{\mathcal{D}}{\preccurlyeq} \mathsf{WRC}^G_{p,q}. \tag{8}$$

We mention that (provided G is connected) the specifications (6) and (7) differ with positive probability if and only if the event of having more than one infinite connected component has positive probability. By an application of the uniqueness theorem of Burton and Keane [11], we get in the case where G is the usual $\mathbb{Z}^d$ lattice (and more generally when G is a transitive amenable graph—see Section 2.5 for a definition) that the number of infinite clusters is at most one, FRC-a.s. as well as WRC-a.s. It follows that, in this case, both FRC and WRC are simultaneously DLR random-cluster measures and DLR wired random-cluster measures.

We finally state a few more well-known stochastic inequalities for random-cluster measures that we shall have occasion to use: If $p_1 \le p_2$ and $p_1/[(1-p_1)q_1] \le p_2/[(1-p_2)q_2]$, then

$$\mathsf{FRC}^G_{p_1,q_1} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{FRC}^G_{p_2,q_2} \tag{9}$$

and

$$\mathsf{WRC}^G_{p_1,q_1} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{WRC}^G_{p_2,q_2}. \tag{10}$$

In particular, if $p_1 \le p_2$, then

$$\mathsf{FRC}^G_{p_1,q} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{FRC}^G_{p_2,q} \tag{11}$$

and

$$\mathsf{WRC}^G_{p_1,q} \overset{\mathcal{D}}{\preccurlyeq} \mathsf{WRC}^G_{p_2,q}. \tag{12}$$

2.4. *The Potts model on infinite graphs.* Let $G = (V, E)$ be infinite and locally finite and let $\{G_i := (V_i, E_i)\}_{i=1}^{\infty}$ be as in the previous subsection. For $q \in \{2, 3, \ldots\}$ and $\beta \ge 0$, define probability measures $\{\mathsf{FPt}^{G,i}_{q,\beta}\}_{i=1}^{\infty}$ on $\{1, \ldots, q\}^V$ in such a way that the projection of $\mathsf{FPt}^{G,i}_{q,\beta}$ on $\{1, \ldots, q\}^{V_i}$ equals $\mathsf{Pt}^{G_i}_{q,\beta}$, and the spins on $V \setminus V_i$ are i.i.d. uniformly distributed on $\{1, \ldots, q\}$ and independent of the spins on V_i. It turns out that $\mathsf{FPt}^{G,i}_{q,\beta}$ has a limiting distribution $\mathsf{FPt}^G_{q,\beta}$ as $i \to \infty$.

Also, for a fixed spin $r \in \{1, \ldots, q\}$, define $\mathsf{WPt}^{G,i}_{q,\beta,r}$ to be the distribution corresponding to picking $X \in \{1, \ldots, q\}^V$ by letting $X(V \setminus V_i) \equiv r$ and letting $X(V_i)$ be distributed according to $\mathsf{Pt}^{G_i}_{q,\beta}$ *conditioned on the event that* $X(\partial V_i) \equiv r$. Again, $\mathsf{WPt}^{G,i}_{q,\beta,r}$ has a limiting distribution as $i \to \infty$, which we denote $\mathsf{WPt}^G_{q,\beta,r}$.

The existence of the limiting distributions $\mathsf{FPt}^G_{q,\beta}$ and $\mathsf{WPt}^G_{q,\beta,r}$ are nontrivial results, and, in fact, the shortest route to proving them goes via the stochastic monotonicity arguments for the random-cluster model outlined in Section 2.3 and then using Propositions 2.2 and 2.3 below.

A probability measure μ on $\{1,\dots,q\}^V$ is said to be a Gibbs measure (in the DLR sense) for the q-state Potts model on G at inverse temperature β if it admits conditional distributions such that, for all $v \in V$, all $r \in \{1,\dots,q\}$ and all $\omega \in \{1,\dots,q\}^{V\setminus\{v\}}$, we have

$$\mu\big(X(v)=r \mid X(V\setminus\{v\})=\omega\big)=\frac{1}{Z}\exp\Bigg(-2\beta\sum_{[v,y]\in E}\mathbf{1}_{\{\omega(v)\neq\omega(y)\}}\Bigg), \tag{13}$$

where the normalizing constant Z may depend on v and ω but not on r. It turns out that $\mathsf{FPt}^G_{q,\beta}$ and $\mathsf{WPt}^G_{q,\beta,r}$ are both Gibbs measures in this sense. Another Gibbs measure of particular interest is

$$\mathsf{WPt}^G_{q,\beta} := \frac{1}{q}\sum_{r=1}^{q}\mathsf{WPt}^G_{q,\beta,r}.$$

The following extensions of Proposition 2.1 provide the relations between FRC and WRC on the one hand, and FPt and WPt on the other.

PROPOSITION 2.2. *Fix an infinite locally finite graph G, an integer $q \geq 2$ and $p \in [0,1]$. Pick a random edge configuration $X \in \{0,1\}^E$ according to $\mathsf{FRC}^G_{p,q}$. Then, for each connected component $\mathcal{C}$ of X, pick a spin uniformly from $\{1,\dots,q\}$ and assign this spin to all vertices of $\mathcal{C}$. Do this independently for different connected components. The $\{1,\dots,q\}^V$-valued random spin configuration arising from this procedure is then distributed according to the Gibbs measure $\mathsf{FPt}^G_{q,\beta}$ for the q-state Potts model on G at inverse temperature $\beta := -\frac{1}{2}\log(1-p)$.*

PROPOSITION 2.3. *Let G, p, q and β be as in Proposition 2.2. Pick a random edge configuration $X \in \{0,1\}^E$ according to the random-cluster measure $\mathsf{WRC}^G_{p,q}$. Then, for each* finite *connected component $\mathcal{C}$ of X, pick a spin uniformly from $\{1,\dots,q\}$ and assign this spin to all vertices of $\mathcal{C}$. Do this independently for different connected components. Finally, assign value r to all vertices of infinite connected components. The $\{1,\dots,q\}^V$-valued random spin configuration arising from this procedure is then distributed according to the Gibbs measure $\mathsf{WPt}^G_{q,\beta,r}$ for the q-state Potts model on G at inverse temperature β.*

2.5. *Some classes of infinite graphs.* The class of all infinite locally finite graphs is often too large to obtain the most interesting results for the random-cluster model (and other stochastic models on graphs; see, e.g., [35] for a survey), and indeed most of our results will concern more restrictive classes of graphs. Here we recall some such classes.

Let, as usual, $G = (V, E)$ be an infinite locally finite graph. The number of edges incident to a vertex x is called the *degree* of x. The graph G is said to be *regular* if every vertex has the same degree.

A *graph automorphism* of G is a bijective mapping $\gamma : V \to V$ with the property that, for all $x, y \in V$, we have $[\gamma x, \gamma y] \in E$ if and only if $[x, y] \in E$. Write $\mathrm{Aut}(G)$ for the group of all graph automorphisms of G. To each $\gamma \in \mathrm{Aut}(G)$, there is a corresponding mapping $\tilde{\gamma} : E \to E$ defined by $\tilde{\gamma}[x, y] := [\gamma x, \gamma y]$. The graph G is said to be *transitive* if and only if for any $x, y \in V$ there exists $\gamma \in \mathrm{Aut}(G)$ such that $\gamma x = y$. More generally, G is said to be *quasi-transitive* if V can be partitioned into finitely many sets $V_1, \dots, V_k$ such that, for any $i \in \{1, \dots, k\}$ and any $x, y \in V_i$, there exists a $\gamma \in \mathrm{Aut}(G)$ such that $\gamma x = y$.

A probability measure μ on $\{0, 1\}^E$ is said to be *automorphism invariant* if, for any n, any $e_1, \dots, e_n \in E$, any $i_1, \dots, i_n \in \{0, 1\}$ and any graph automorphism γ, we have

$$\mu\big(X(e_1) = i_1, \dots, X(e_n) = i_n\big) = \mu\big(X\big(\tilde{\gamma}(e_1)\big) = i_1, \dots, X\big(\tilde{\gamma}(e_n)\big) = i_n\big).$$

It follows from the construction of the free and wired random-cluster measures FRC and WRC [in particular, from the independence of the choice of $\{G_i = (V_i, E_i)\}_{i=1}^{\infty}$] that both measures are automorphism invariant. It turns out that automorphism invariance has far-reaching consequences for percolation processes on various classes of transitive graphs; see, for example, [6], [11], [28] and [37].

Two important properties, which may or may not hold for a given quasi-transitive graph, are amenability and unimodularity, which we review next. We say that a graph G is *amenable* if

$$\inf \frac{|\partial W|}{|W|} = 0,$$

where the infimum ranges over all finite $W \subset V$ and $|\cdot|$ denotes cardinality. There are various alternative definitions of amenability of a graph, which coincide for quasi-transitive graphs (and more generally for graphs of bounded degree), but not in general.

For any graph G and $x \in V$, define the *stabilizer* $S(x)$ as the set of graph automorphisms that fix x, that is,

$$S(x) := \big\{\gamma \in \mathrm{Aut}(G); \gamma x = x\big\}.$$

For $x, y \in V$, define

$$S(x)y := \big\{z \in V; \exists\ \gamma \in S(x) \text{ such that } \gamma y = z\big\}.$$

When $\mathrm{Aut}(G)$ is given the weak topology generated by its action on V, all stabilizers are compact because G is locally finite and connected. We say that G is *unimodular* if, for all x, y in the same orbit of $\mathrm{Aut}(G)$ (in the transitive case, this just means for all $x, y \in V$), we have the symmetry

$$|S(x)y| = |S(y)x|.$$

An important class of transitive graphs is the class of Cayley graphs. If Γ is a finitely generated group with generating set $\{g_1, \ldots, g_n\}$, then the *Cayley graph* associated with Γ and that particular set of generators is the (unoriented) graph $G = (V, E)$ with vertex set $V := \Gamma$ and edge set

$$E := \{[x, y]; x, y \in \Gamma, \exists\, i \in \{1, \ldots, n\} \text{ such that } xg_i = y\}.$$

Most examples of graphs that have been studied in percolation theory are Cayley graphs. These include $\mathbb{Z}^d$ (which, with a slight abuse of notation, is short for the graph with vertex set $\mathbb{Z}^d$ and edges connecting pairs of vertices at Euclidean distance 1 from each other) and the regular tree $\mathbf{T}_n$ in which every vertex has exactly $n + 1$ neighbors. The graph $\mathbb{Z}^d$ is amenable, while $\mathbf{T}_n$ is nonamenable for $n \geq 2$. Also studied are certain tilings of the hyperbolic plane (see Section 4), and further examples can be obtained, for example, by taking Cartesian products of other Cayley graphs (such as $\mathbf{T}_n \times \mathbb{Z}$, the much-studied example of Grimmett and Newman [26]).

All Cayley graphs are unimodular. An example, due to Trofimov [44], of a transitive graph that is nonunimodular (and hence not a Cayley graph) may be obtained by taking the binary tree $\mathbf{T}_2$, fixing a so-called topological end ζ (loosely speaking, a direction to infinity in the tree) and adding an edge between each vertex and its ζ-grandparent.

3. The four critical values. Let, as usual, $G = (V, E)$ be infinite and locally finite. A probability measure μ on $\{0, 1\}^E$ is said to be *insertion tolerant* if, for any $e \in E$ and almost every $\xi \in \{0, 1\}^{E \setminus \{e\}}$, the conditional μ-probability that e is open, given the configuration ξ on $\{0, 1\}^{E \setminus \{e\}}$, is strictly positive. Newman and Schulman [38] showed that for any automorphism-invariant insertion-tolerant percolation process on $\mathbb{Z}^d$ the number of infinite clusters is a.s. 0, 1 or ∞. It has been observed by several authors (see, e.g., [4]) that this result (as well as its proof in [38]) extends to the class of quasi-transitive connected graphs.

Suppose that G is quasi-transitive and connected. The Newman–Schulman result then applies to $\mathsf{FRC}^G_{p,q}$ and $\mathsf{WRC}^G_{p,q}$ because (6) and (7) imply that the two measures are insertion tolerant whenever $p \in (0, 1)$. Furthermore, $\mathsf{FRC}^G_{p,q}$ and $\mathsf{WRC}^G_{p,q}$ are ergodic; this was proved in [10] for FRC and in [8] for both measures. A simple proof of the stronger property that the tail σ-field is trivial appears in [35]. Ergodicity shows that, for each fixed p and q, the number of infinite clusters is an a.s. constant (which, however, need not be the same for $\mathsf{FRC}^G_{p,q}$ and for $\mathsf{WRC}^G_{p,q}$). Hence, given G and q, the set $[0, 1]$ of possible values for p can be partitioned into three sets according to whether the $\mathsf{FRC}^G_{p,q}$-a.s. number of infinite clusters is 0, 1 or ∞, and similarly it can be partitioned via $\mathsf{WRC}^G_{p,q}$. From (11) and (12), we can immediately deduce that the set of p for which the number of infinite clusters is 0 is an interval containing 0. In other words, there exist critical values $p_c^{\text{free}} := p_c^{\text{free}}(G, q)$ and $p_c^{\text{wired}} := p_c^{\text{wired}}(G, q)$ such that

$$\mathsf{FRC}_{p,q}^{G}(\exists \text{ at least one infinite cluster}) = \begin{cases} 0, & \text{for } p < p_c^{\text{free}}, \\ 1, & \text{for } p > p_c^{\text{free}}, \end{cases} \tag{14}$$

and

$$\mathsf{WRC}_{p,q}^{G}(\exists \text{ at least one infinite cluster}) = \begin{cases} 0, & \text{for } p < p_c^{\text{wired}}, \\ 1, & \text{for } p > p_c^{\text{wired}}. \end{cases} \tag{15}$$

The question of how the interval above p_c^{free} (p_c^{wired}) is split up according to whether the number of infinite clusters is 1 or ∞ is more intricate. Does it split nicely into two intervals, or are the sets more complicated? A proof is given in [35], Proposition 5.2, that in the quasi-transitive unimodular case the uniqueness sets are simply intervals. Presumably, this holds whenever G is quasi-transitive. A similar proof shows that

$$\mathsf{FRC}_{p,q}^{G}(\exists \text{ a unique infinite cluster}) \le \mathsf{WRC}_{p,q}^{G}(\exists \text{ a unique infinite cluster}). \tag{16}$$

Thus, if G is quasi-transitive and unimodular, there exist critical values $p_u^{\text{free}} := p_u^{\text{free}}(G, q)$ and $p_u^{\text{wired}} := p_u^{\text{wired}}(G, q)$ such that

$$\mathsf{FRC}_{p,q}^{G}(\exists \text{ a unique infinite cluster}) = \begin{cases} 0, & \text{for } p < p_u^{\text{free}}, \\ 1, & \text{for } p > p_u^{\text{free}}, \end{cases} \tag{17}$$

and

$$\mathsf{WRC}_{p,q}^{G}(\exists \text{ a unique infinite cluster}) = \begin{cases} 0, & \text{for } p < p_u^{\text{wired}}, \\ 1, & \text{for } p > p_u^{\text{wired}}. \end{cases} \tag{18}$$

Summarizing (14), (15), (17) and (18), we have (for G connected, quasi-transitive and unimodular) four critical values p_c^{wired}, p_c^{free}, p_u^{wired}, $p_u^{\text{free}} \in [0, 1]$ such that the $\mathsf{FRC}_{p,q}^{G}$-a.s. number of infinite clusters equals

$$\begin{cases} 0, & \text{for } p < p_c^{\text{free}}, \\ \infty, & \text{for } p \in (p_c^{\text{free}}, p_u^{\text{free}}), \\ 1, & \text{for } p > p_u^{\text{free}}, \end{cases}$$

and the $\mathsf{WRC}_{p,q}^{G}$-a.s. number of infinite clusters equals

$$\begin{cases} 0, & \text{for } p < p_c^{\text{wired}}, \\ \infty, & \text{for } p \in (p_c^{\text{wired}}, p_u^{\text{wired}}), \\ 1, & \text{for } p > p_u^{\text{wired}}. \end{cases}$$

We now consider whether there is an infinite cluster at $p_c(q)$. It is known that there is none for $q = 1$ on nonamenable quasi-transitive unimodular graphs (see [6] and [7]). On the other hand, it is known that there can be infinitely many infinite clusters for $q > 2$ on the Cayley graphs $\mathbf{T}_n$ for $n \ge 2$ with respect to the wired random-cluster measure; see [14] and [27]. While we do not have a criterion that settles the question completely, we have the following partial results.

THEOREM 3.1. *Let G be a quasi-transitive nonamenable unimodular graph and $q \geq 1$. Then there is no infinite cluster $\mathsf{FRC}^G_{p_c^{\text{free}}(q),q}$-a.s. Also, the following are equivalent*:

(i) *There is no infinite cluster $\mathsf{WRC}^G_{p_c^{\text{wired}}(q),q}$-a.s.*

(ii) *For every edge $e \in G$, the function $p \mapsto \mathsf{WRC}^G_{p,q}(X(e) = 1)$ is continuous from the left at $p_c^{\text{wired}}(q)$.*

(iii) $\mathsf{FRC}^G_{p_c^{\text{wired}}(q),q} = \mathsf{WRC}^G_{p_c^{\text{wired}}(q),q}$.

PROOF. Fix an edge $e = [x, y]$. Let $Q^{\text{free}}(p) := \mathsf{FRC}^G_{p,q}(X(e) = 1)$ and $Q^{\text{wired}}(p) := \mathsf{WRC}^G_{p,q}(X(e) = 1)$. Now

$$Q^{\text{free}}(p) = \lim_{i\to\infty} \mathsf{FRC}^{G,i}_{p,q}\bigl(X(e) = 1\bigr)$$

by definition. Since the latter probabilities (before the limit is taken) are rational functions in p and q, they are continuous at all p. Since they are increasing in p and increase to their limit, we obtain the left-continuity of $Q^{\text{free}}(p)$ at all p.

We need the existence of an invariant coupling (X, X') that witnesses the stochastic domination $\mathsf{FRC}_{p_c^{\text{free}}(q),q} \overset{\mathcal{D}}{\succcurlyeq} \mathsf{FRC}_{p,q}$, and similarly for WRC. Such couplings are constructed in [30]. For $p < p_c^{\text{free}}(q)$, the probability that

$$^{\text{free}}X^G_{p_c^{\text{free}}(q),q}(e) = 1 \quad \text{and} \quad ^{\text{free}}X^G_{p,q}(e) = 0 \tag{19}$$

in any such coupling equals $Q^{\text{free}}(p_c^{\text{free}}(q)) - Q^{\text{free}}(p)$. Thus, left-continuity of $Q^{\text{free}}(p)$ at $p = p_c^{\text{free}}(q)$ implies that the probability of (19) tends to 0 as $p \uparrow p_c^{\text{free}}(q)$. Therefore minor modifications of the proofs in [7] show that there is no infinite cluster $\mathsf{FRC}^G_{p_c^{\text{free}}(q),q}$-a.s. This establishes the first claim.

Now we consider the equivalences. A similar argument to the above shows that (ii) implies (i). The other implications hold for all graphs. That (i) implies (iii) is due to [1]; the reasoning is sketched in the proof of Proposition 3.8 below. If (iii) holds, then $\mathsf{FRC}_{p,q} = \mathsf{WRC}_{p,q}$ for all $p \leq p_c^{\text{wired}}$ by [1] again. Therefore $Q^{\text{wired}}(p) = Q^{\text{free}}(p)$ for $p \leq p_c^{\text{wired}}$ and the continuity of $Q^{\text{free}}(p)$ implies (ii) as above. $\square$

Given a spin configuration $\omega \in \{1, \ldots, q\}^V$ and an edge configuration $\xi \in \{0, 1\}^E$, we may partition V into *connected single-spin components*, meaning that x and y are in the same connected single-spin component if and only if there is a path from x to y in which all vertices have the same spin and all edges are open. The following facts relate the four critical values to corresponding phenomena for the Potts model.

PROPOSITION 3.2. *Let G be any graph, $\beta > 0$, $q \geq 1$ and $p := 1 - e^{-2\beta}$.*

(i) *There is no infinite cluster $\mathsf{WRC}_{p,q}$-a.s. iff there is a unique Gibbs measure for the Potts model with the corresponding parameters (q, β).*

(ii) *Let $\omega \in \{1, \dots, q\}^V$ be chosen according to $\mathsf{FPt}_{q,\beta}$ and independently let $\xi \in \{0, 1\}^E$ be chosen according to Bernoulli(p) percolation. There is a unique infinite cluster $\mathsf{FRC}_{p,q}$-a.s. iff (ω, ξ) a.s. produces a unique infinite connected single-spin component.*

(iii) *Let $\omega \in \{1, \dots, q\}^V$ be chosen according to $\mathsf{WPt}_{q,\beta}$ and independently let $\xi \in \{0, 1\}^E$ be chosen according to Bernoulli(p) percolation. There is a unique infinite cluster $\mathsf{WRC}_{p,q}$-a.s. iff (ω, ξ) a.s. produces a unique infinite connected single-spin component.*

(iv) *If there is a unique infinite cluster $\mathsf{FRC}_{p,q}$-a.s., then $\mathsf{FPt}_{q,\beta}$ is not extremal among all Gibbs measures.*

(v) *Suppose that G is quasi-transitive. If there is a unique infinite cluster $\mathsf{FRC}_{p,q}$-a.s., then $\mathsf{FPt}_{q,\beta}$ is not extremal among invariant Gibbs measures. If G is also unimodular, then the converse holds; in fact, if there is not a unique infinite cluster $\mathsf{FRC}_{p,q}$-a.s., then $\mathsf{FPt}_{q,\beta}$ is ergodic, that is, extremal among all invariant probability measures.*

PROOF. Part (i) is essentially due to Aizenman, Chayes, Chayes and Newman [1] (or see [22]). Parts (ii) and (iii) follow immediately from the coupling of random-cluster and Potts models underlying Propositions 2.2 and 2.3.

Part (iv) follows from (ii): If there is a unique infinite component $\mathsf{FRC}_{p,q}$-a.s., then let (ω, ξ) have the distribution $\mathsf{FPt}_{q,\beta} \times \mathsf{RC}_{p,1}$, as in (ii). By (ii), we may define $r(\omega, \xi)$ to be the spin of the unique infinite single-spin component determined by (ω, ξ). Let $\mathcal{C}(\omega)$ be the collection of maximal connected subgraphs of G whose vertices have a common spin; this does not depend on ξ. Then $r(\omega, \xi)$ is the spin of the unique graph K in $\mathcal{C}(\omega)$ such that $K \cap \xi$ contains an infinite component with positive probability (in ξ). In particular, $r(\omega, \xi)$ depends only on ω a.s., and it is a tail random variable that is not trivial. Thus we have shown that the tail σ-field of $\mathsf{FPt}_{q,\beta}$ is not trivial. This is equivalent to nonextremality among all Gibbs measures by [21], Theorem 7.7.

The first part of (v) is due to [41], Theorem 4.2. The converse of (iv) is not true in general, as is well known on trees (see, e.g., [9] or [17]). However, if G is quasi-transitive and unimodular and if there is not a unique infinite cluster $\mathsf{FRC}_{p,q}$-a.s., then, by [37], Theorem 4.1 and Lemma 6.4, extended from the transitive case to the quasi-transitive case, $\mathsf{FPt}_{q,\beta}$ is ergodic, which is the same as extremal among all invariant measures. □

How do the four critical values relate to each other? From the definitions it is immediate that

$$p_c^{\text{free}} \leq p_u^{\text{free}} \tag{20}$$

and

$$p_c^{\mathrm{wired}} \le p_u^{\mathrm{wired}}. \tag{21}$$

By (8) and (16), we also have

$$p_c^{\mathrm{wired}} \le p_c^{\mathrm{free}} \tag{22}$$

and

$$p_u^{\mathrm{wired}} \le p_u^{\mathrm{free}}. \tag{23}$$

All of (20)–(23) can reduce to equalities; this happens, for example, whenever G is amenable. To see this for (20) and (21), just note the well-known fact that the Burton–Keane ([11] and [20]) encounter-point argument (for showing uniqueness of the infinite cluster under the insertion tolerance condition) goes through in the amenable setting. For (22) and (23), see Grimmett [24] and Jonasson [31], where it is shown that, for all $q \ge 1$, there are at most countably many p such that $\mathsf{FRC}^G_{p,q} \neq \mathsf{WRC}^G_{p,q}$.

The inequalities can also be strict. To get examples with strict inequalities in (20) and (21), one can take $q := 1$ and G to be any of the nonamenable transitive unimodular graphs that are known to have a "middle phase" for i.i.d. percolation (i.e., a positive-length interval of values of p that give rise to infinitely many infinite clusters); see, for example, [35]. Using the ideas in the proof of [35], Proposition 5.2, and the inequalities (9) and (10), it is not hard to show that one can take q to be slightly larger than 1 in all such examples. For an example where the inequality in (22) is strict, we can simply take G to be the regular tree $\mathbf{T}_n$ with $n \ge 2$ and $q > 2$ (see, e.g., [27]) or take any nonamenable regular graph with q sufficiently large [this follows from [31], Theorem 1.2(a), in combination with (8)]. Finally, for an example where (23) is strict, we refer to Section 4.

The inequalities (20)–(23) say nothing about the relationship between p_u^{wired} and p_c^{free}. Here it is possible to get a strict inequality in either direction. Examples with $p_c^{\mathrm{free}} < p_u^{\mathrm{wired}}$ can be obtained in the same way as for (20) and (21); see Proposition 4.13 below for explicit bounds on certain graphs. To get an example with the reverse inequality $p_u^{\mathrm{wired}} < p_c^{\mathrm{free}}$ is more intricate and is the topic of the next section. Note that any such example also gives strict inequality in (22) and in (23).

QUESTION 3.3. We say that G has *one end* if the complement of every finite subset has exactly one infinite component. If G is any nonamenable quasi-transitive graph with one end and $q \ge 1$, are the inequalities (20) and (21) necessarily strict?

Of course, when $q = 1$, a famous conjecture of [4] asserts a positive answer.

If G is a graph drawn in the plane in such a way that edges do not cross and such that each bounded set in the plane contains only finitely many vertices of G, then G is said to be *properly embedded*. We shall always assume without mention that planar graphs are properly embedded. (The graphs we shall consider in the next section can be embedded in the hyperbolic plane more geometrically than in the Euclidean plane, but topologically and combinatorially, this is not different from Euclidean embeddings.) If G is a planar (multi)graph, then the *planar dual* $G^\dagger$ of G (really, of this particular embedding of G) is the (multi)graph formed as follows: The vertices of $G^\dagger$ are the faces formed by G. Two faces of $G^\dagger$ are joined by an edge precisely when they share an edge in G. Thus $E(G)$ and $E(G^\dagger)$ are in a natural one-to-one correspondence. Furthermore, if one draws each vertex of $G^\dagger$ in the interior of the corresponding face of G and each edge of $G^\dagger$ so that it crosses the corresponding edge of G, then the dual of $G^\dagger$ is G. For planar graphs, we shall always assume that G and its planar dual $G^\dagger$ are locally finite, whence each graph has one end.

Let G be a planar graph. If μ is a probability measure on $\{0,1\}^E$, we associate a *dual* measure $\mu^\dagger$ on $\{0,1\}^{E^\dagger}$ as follows. Given $e \in E$, let $e^\dagger$ be the edge in $E^\dagger$ that crosses e. Given $\xi \in \{0,1\}^E$, let $\tilde{\xi} \in \{0,1\}^{E^\dagger}$ be the function $e^\dagger \mapsto 1-\xi(e)$. For a Borel set $A \subset \{0,1\}^E$, write $\tilde{A} := \{\tilde{\xi}; \xi \in A\}$. Then $\mu^\dagger$ is defined by $\mu(A) = \mu^\dagger(\tilde{A})$. Our next proposition is more or less well known (see, e.g., [13] and [45]), but perhaps has not been stated in this particular form before. For completeness, we provide the simple proof here.

PROPOSITION 3.4. *For any planar graph G, $\mathsf{FRC}^G_{p,q}$ is dual to $\mathsf{WRC}^{G^\dagger}_{p',q}$ if*

$$p' = \frac{(1-p)q}{p+(1-p)q}. \tag{24}$$

PROOF. Suppose first that G is a finite graph. For any $\xi \in \{0,1\}^E$, write $\tilde{\xi} := E^\dagger \setminus \xi^\dagger$ as above. Euler's formula applied to the graph $\tilde{G} := (V^\dagger, \tilde{\xi})$ says that

$$|V^\dagger| - |\tilde{\xi}| + \|\xi\| = 1 + \|\tilde{\xi}\|$$

since the number of faces of $\tilde{G}$ is equal to $\|\xi\|$. Thus

$$\begin{aligned}
\mathsf{RC}^G_{p,q}(\xi) &= Z^{-1} p^{|\xi|}(1-p)^{|E\setminus\xi|} q^{\|\xi\|} \\
&= Z^{-1} p^{|E^\dagger\setminus\tilde{\xi}|}(1-p)^{|\tilde{\xi}|} q^{1+\|\tilde{\xi}\|-|V^\dagger|+|\tilde{\xi}|} \\
&= Z^{-1} q^{1-|V^\dagger|} p^{|E^\dagger\setminus\tilde{\xi}|}\big[(1-p)q\big]^{|\tilde{\xi}|} q^{\|\tilde{\xi}\|} \\
&= \tilde{Z}^{-1}(1-p')^{|E^\dagger\setminus\tilde{\xi}|} p'^{|\tilde{\xi}|} q^{\|\tilde{\xi}\|} \\
&= \mathsf{RC}^{G^\dagger}_{p',q}(\tilde{\xi}),
\end{aligned}$$

where Z and $\tilde{Z}$ are normalizing constants that do not depend on ξ. Thus $\mathsf{RC}^{G}_{p,q}$ is dual to $\mathsf{RC}^{G^\dagger}_{p',q}$.

Now let V_i be a sequence of increasing finite subsets of V such that the faces of $G(V_i)$ are faces of G, except for the outer face, of course. Then we have seen that $\mathsf{RC}^{G_i}_{p,q}$ is dual to $\mathsf{RC}^{G_i^\dagger}_{p',q}$. Thus the general result follows by taking weak limits. □

In consequence, the methods of Benjamini and Schramm [5] show the following proposition. The paper [5] dealt only with transitive graphs, but the methods work just as well given the fact that quasi-transitive planar graphs with one end are unimodular; this fact is proved in [36].

PROPOSITION 3.5. *Let G be a planar nonamenable quasi-transitive graph and let p' be as in* (24). *In the natural coupling of $\mathsf{FRC}^{G}_{p,q}$ and $\mathsf{WRC}^{G^\dagger}_{p',q}$ as dual measures, the number of infinite clusters with respect to each is a.s. one of the following*: $(0, 1)$, $(1, 0)$ *or* (∞, ∞).

Write

$$h(x) := x/(1-x). \tag{25}$$

COROLLARY 3.6. *For any planar nonamenable quasi-transitive graph G,*

$$h\big(p_{\mathrm{c}}^{\mathrm{wired}}(G,q)\big)h\big(p_{\mathrm{u}}^{\mathrm{free}}(G^\dagger,q)\big) = h\big(p_{\mathrm{c}}^{\mathrm{free}}(G,q)\big)h\big(p_{\mathrm{u}}^{\mathrm{wired}}(G^\dagger,q)\big) = q,$$

$$0 < p_{\mathrm{c}}^{\mathrm{wired}}(G,q) \le p_{\mathrm{c}}^{\mathrm{free}}(G,q) < 1 \quad \textit{and} \quad 0 < p_{\mathrm{u}}^{\mathrm{wired}}(G,q) \le p_{\mathrm{u}}^{\mathrm{free}}(G,q) < 1.$$

PROOF. Proposition 3.5 shows that there is no infinite cluster a.s. with respect to the free measure iff there is a unique infinite cluster a.s. with respect to the dual wired measure. Therefore $p_{\mathrm{u}}^{\mathrm{wired}}(G^\dagger,q) = (p_{\mathrm{c}}^{\mathrm{free}}(G,q))'$ in the notation of (24). Some algebra shows that this is the same as $h(p_{\mathrm{c}}^{\mathrm{free}}(G,q))h(p_{\mathrm{u}}^{\mathrm{wired}}(G^\dagger,q)) = q$. A similar proof shows the other equation.

It is well known that $0 < p_{\mathrm{c}}(G) := p_{\mathrm{c}}(G,1) < 1$ under the present assumptions [35]. From (9) and (10), it follows that the same holds for $p_{\mathrm{c}}^{\mathrm{wired}}(G,q)$ and $p_{\mathrm{c}}^{\mathrm{free}}(G,q)$ when $q > 1$. The same now follows for the uniqueness critical points by the equations just established. □

COROLLARY 3.7. *Let G be a planar nonamenable quasi-transitive graph with one end. Then there is $\mathsf{WRC}^{G}_{p_{\mathrm{u}}^{\mathrm{wired}}(G,q),q}$-a.s. a unique infinite cluster.*

PROOF. In light of Theorem 3.1, there is no infinite cluster $\mathsf{FRC}^{G^\dagger}_{p_c^{\mathrm{free}}(G^\dagger,q),q}$-a.s. Hence, by Proposition 3.5 and Corollary 3.6, there is a unique infinite cluster $\mathsf{WRC}^{G}_{p_u^{\mathrm{wired}}(G,q),q}$-a.s. $\square$

The methods of Grimmett [25] show that, for any quasi-transitive G, the critical points $p_c^{\mathrm{wired}}(q)$ and $p_c^{\mathrm{free}}(q)$ are continuous and strictly increasing functions of q as long as $p_c(1) < 1$, and similarly $p_u^{\mathrm{wired}}(q)$ and $p_u^{\mathrm{free}}(q)$ are continuous and strictly increasing functions of q as long as $p_u(1) < 1$. When G is a planar regular graph with regular dual, [5] shows that $p_c(G) < p_u(G) := p_u(G,1)$, while Theorem 4.11 below shows that $p_c^{\mathrm{free}}(G,q) > p_u^{\mathrm{wired}}(G,q)$ for large q. Thus there is at least one q for which $p_c^{\mathrm{free}}(G,q) = p_u^{\mathrm{wired}}(G,q)$. If G is isomorphic to its dual, then these critical values are equal to $\sqrt{q}/(\sqrt{q}+1)$ because of Corollary 3.6. We do not know whether this holds for exactly one q; see Question 4.15.

Another natural set of p to examine for fixed q is the set where $\mathsf{FRC}_{p,q} = \mathsf{WRC}_{p,q}$, which is where $\mathsf{FPt}_{q,\beta} = \mathsf{WPt}_{q,\beta}$, as shown in [31], Lemma 4.3. In general, this is not simply an interval, but let us define

$$p_{\mathrm{F=W}}(G) := \sup\{p < 1; \mathsf{FRC}^G_p \neq \mathsf{WRC}^G_p\}.$$

We say that a graph has *bounded fundamental cycle length* if there is a set of (oriented simple) cycles of the graph with bounded length that generates all cycles by addition and subtraction (in the sense of homology). For example, this is the case for Cayley graphs of finite presentations of groups. Recall that G has one end if the complement of every finite subset has exactly one infinite component.

PROPOSITION 3.8. *Let G be any graph.*

(i) *If $p < p_c^{\mathrm{wired}}(G)$, then $\mathsf{FRC}^G_p = \mathsf{WRC}^G_p$.*
(ii) *If $p_c^{\mathrm{wired}}(G) < p < p_u^{\mathrm{free}}(G)$, then $\mathsf{FRC}^G_p \neq \mathsf{WRC}^G_p$.*
(iii) *If G is a graph with one end and bounded fundamental cycle length, then $p_{\mathrm{F=W}}(G) < 1$.*
(iv) *If G is a planar nonamenable quasi-transitive graph with one end, then $p_{\mathrm{F=W}}(G) = p_u^{\mathrm{free}}(G)$.*

PROOF. Part (i) is due to [1], but we recap the short proof here. It suffices to show that $\mathsf{WRC}^G_p \overset{\mathcal{D}}{\preccurlyeq} \mathsf{FRC}^G_p$ if $p < p_c^{\mathrm{wired}}(G)$ or, more generally, if there is no infinite cluster WRC^G_p-a.s. Since there is no infinite cluster, given any ball B about o and any $\varepsilon > 0$, there is a ball B' so that, with probability at least $1-\varepsilon$, there is a unique maximal set $K \subset B'$ such that all of $\partial_E K$ is closed and $B \subset K$. Given that K is such a set, the configuration restricted to $G(K)$ has the distribution $\mathsf{RC}^{G(K)}_p$, which is dominated by the restriction of FRC^G_p to $G(K)$. In particular, this holds for the restriction of the configuration to B. Since ε and B were arbitrary, the result follows.

Part (ii) is due to [31]. Again, the proof is short: If $\mathsf{FRC}_p^G = \mathsf{WRC}_p^G$, then the two measures give the same number of infinite clusters a.s. Furthermore, since the measures are both DLR random-cluster measures and DLR wired random-cluster measures, there is at most one infinite cluster a.s. Hence $p \notin (p_c^{\mathrm{wired}}(G), p_u^{\mathrm{free}}(G))$.

Now let G be any graph with one end and bounded fundamental cycle length. Let t be an upper bound for the lengths of a set of generating cycles. The fundamental theorem of [2] implies that the t-neighborhood of any minimal cutset is connected. Note that, by (9), FRC_p^G dominates Bernoulli(p^*) bond percolation $\mathbf{P}_{p^*}$ with p^* close to 1 when p is close to 1. Consider then a coupling (ξ, ω) with $\xi \supseteq \omega$ such that ξ has distribution FRC_p^G and ω has distribution $\mathbf{P}_{p^*}$. Let ω' consist of those edges e such that all bonds within distance t of e are open in ω; define ξ' similarly with respect to ξ. The percolation ω' dominates a Bernoulli percolation with survival parameter close to 1 by [34] or [37], Remark 6.2. Thus a.s. the *closed* bonds of ω' do not form any infinite cluster if p^* is sufficiently close to 1. Therefore, when p is close to 1, the same holds for ξ'. Choose p so close to 1 that ξ' has no infinite closed clusters. Fix $r \in \mathbb{Z}^+$ and $\varepsilon > 0$. Let B_r be the ball of radius r about o. For any set of sites S, let $K(S)$ be the set of vertices that can be reached from some vertex of S without using an open bond from ξ'. There is a sphere S about o so that the probability of the event $E := \{K(S) \cap B_{r+t} = \varnothing\}$ is at least $1 - \varepsilon$. Since S separates B_r from ∞ as a set of vertices, so does $\partial_E S$ as a set of edges. Hence the same holds for the larger set $K(S)$ on the event E. Let L be the t-neighborhood of $\partial_E K(S)$. Then, on the event E, the set L consists of open edges of ξ and L separates B_r from ∞. Furthermore, some minimal cutset of $\partial_E K(S)$ separates B_r from ∞ and has a connected t-neighborhood, whence L contains a connected open cutset that separates B_r from ∞. Therefore, given E, the configuration ξ restricted to $G(B_r)$ has the distribution WRC_p^{G,B_r} [which means $\mathsf{WRC}_p^{G,i}$ if $G_i = G(B_r)$], which dominates the restriction of WRC_p^G to $G(B_r)$. Since ε and r were arbitrary, part (iii) follows.

Finally, if G is planar, nonamenable and quasi-transitive, consider $p > p_u^{\mathrm{free}}(G)$. Let p' be as in (24). We have $p' < p_c^{\mathrm{wired}}(G^\dagger)$ by Corollary 3.6, whence $\mathsf{FRC}_{p'}^{G^\dagger} = \mathsf{WRC}_{p'}^{G^\dagger}$ by part (i). Because of Proposition 3.4, it follows that $\mathsf{WRC}_p^G = \mathsf{FRC}_p^G$. Hence $p_{\mathrm{F=W}}(G) = p_u^{\mathrm{free}}(G)$ by part (ii). □

REMARK 3.9. The argument of the last paragraph shows that as long as there is a unique infinite cluster $\mathsf{FRC}_{p_u^{\mathrm{free}}}$-a.s., then $\mathsf{WRC}_p^G = \mathsf{FRC}_p^G$, which establishes Conjecture 4.2 of [41] in the planar nonamenable case.

QUESTION 3.10. If G is a quasi-transitive graph and $q > 1$, is the set of $p \in [0, 1]$ where $\mathsf{FRC}_p^G \neq \mathsf{WRC}_p^G$ an interval?

4. Isoperimetric constants and the critical values. To show that there is a Cayley graph G with $p_c^{\text{free}}(q) > p_u^{\text{wired}}(q)$ for some $q > 1$, we shall need an estimate of an isoperimetric constant. In fact, we are able to calculate precisely the necessary isoperimetric constants for planar regular graphs whose dual is also regular (in this case, either the graph or its dual is a Cayley graph; see [12]). Planar duality and Euler's formula will be essential for this.

We shall make use of the following isoperimetric constants. For $K \subseteq V$, recall that $E(K) := \{[x, y] \in E; x, y \in K\}$ and set $E^*(K) := \{[x, y] \in E; x \in K$ or $y \in K\}$. Define $\partial_E K := E^*(K) \setminus E(K)$ and $G(K) := (K, E(K))$. Write

$$\iota'_E(G) := \lim_{N\to\infty} \inf\left\{\frac{|\partial_E K|}{|K|}; K \subset V,\ G(K) \text{ connected},\ N \le |K| < \infty\right\},$$

$$\beta(G) := \lim_{N\to\infty} \inf\left\{\frac{|K|}{|E(K)|}; K \subset V,\ G(K) \text{ connected},\ N \le |K| < \infty\right\},$$

$$\delta(G) := \lim_{N\to\infty} \sup\left\{\frac{|K|}{|E^*(K)|}; K \subset V,\ G(K) \text{ connected},\ N \le |K| < \infty\right\}.$$

We write d_G for the degree of vertices in G when G is regular. We note that $\beta(G) = 2/\alpha(G)$, with $\alpha(G)$ defined as in [6], except that α was defined with an infimum, rather than a lim inf. In any case, when G is regular,

$$\beta(G) = \frac{2}{d_G - \iota'_E(G)} \tag{26}$$

and

$$\delta(G) = \frac{2}{d_G + \iota'_E(G)}. \tag{27}$$

It is shown in [6] that, when G is transitive,

$$\iota'_E(G) = \inf\left\{\frac{|\partial_E K|}{|K|}; K \subset V \text{ finite and nonempty}\right\}.$$

[The right-hand side is denoted $\iota_E(G)$ there.] Thus, when G is transitive, we have that

$$\delta(G) = \sup\left\{\frac{|K|}{|E^*(K)|}; K \subset V \text{ finite and nonempty}\right\}. \tag{28}$$

Recall from Section 2.5 that G is called quasi-transitive if the vertex set of G decomposes into a finite number of orbits under the action of $\text{Aut}(G)$. Note that G is quasi-transitive iff $G^\dagger$ is quasi-transitive.

The estimate that we shall need is embodied in Corollary 4.5, but the precise combinatorial calculation is the following.

THEOREM 4.1. *If G is a planar regular graph with regular dual $G^\dagger$, then*

$$\iota'_E(G) = (d_G - 2)\sqrt{1 - \frac{4}{(d_G - 2)(d_{G^\dagger} - 2)}}.$$

REMARK 4.2. In this case, G and $G^\dagger$ are transitive. This is folklore. Since we have been unable to find a suitable reference, we include a proof here. First, recall the existence of tessellations by *congruent* polygons (in the Euclidean or hyperbolic plane, as necessary). It is easy to see that the edge graphs of any two such tessellations of the same type are isomorphic, by going out ring by ring around a starting polygon, and thus that such edge graphs are transitive. Now we assert that any (proper) tessellation of a plane with degree d and codegree $d^\dagger$ has an edge graph that is isomorphic to the edge graph of the corresponding tessellation above. In case $(d-2)(d^\dagger - 2) = 4$, we replace each face by a congruent copy of a flat polygon; in case $(d-2)(d^\dagger - 2) > 4$, replace it by a congruent copy of a regular hyperbolic polygon (with curvature -1) of $d^\dagger$ sides and interior angles $2\pi/d$; if $(d-2)(d^\dagger - 2) < 4$, replace it by a congruent copy of a regular spherical polygon (with curvature $+1$) of $d^\dagger$ sides and interior angles $2\pi/d$. Glue these together along the edges. We get a Riemannian surface of curvature 0, -1 or $+1$, correspondingly, that is homeomorphic to the plane since our assumption is that the plane is the union of the faces, edges and vertices of the tessellation, without needing any limit points. Riemann's theorem says that the surface is isometric to either the Euclidean plane or the hyperbolic plane (the spherical case is impossible). That is, we now have a tessellation by congruent polygons. (One could also prove the existence statement in a similar manner.)

REMARK 4.3. Contrary to what one might first expect, we believe that combinatorial balls never give the best isoperimetric constants when G is a nonamenable planar transitive graph with one end. For example, for the isoperimetric constant $\iota'_E(G)$, we believe that $\liminf_n |\partial_E B_n|/|B_n| > \iota'_E(G)$, where B_n is the ball of radius n about o. In many cases, this follows from the formulas of [18]. For instance, suppose that

$$\theta := \lim_{n\to\infty} \frac{|B_{n+1}|}{|B_n|}$$

exists. (This is not the case for all Cayley graphs; see [23].) Then

$$\theta - 1 \le \liminf_{n\to\infty} |\partial_E B_n|/|B_n|.$$

Thus, if $\theta - 1 > \iota'_E(G)$, then we may conclude that $\liminf_{n\to\infty} |\partial_E B_n|/|B_n| > \iota'_E(G)$. For example, if $d_{G^\dagger} = 6$, in which case G is always a Cayley graph (see

[12]), then Theorem 4.1 shows that $\iota'_E(G) = \sqrt{(d_G-2)(d_G-3)}$. On the other hand, [18] shows that

$$\sum_{n\geq 0} |B_n \setminus B_{n-1}| z^n = \frac{z^3+2z^2+2z+1}{z^3+(2-d_G)(z^2+z)+1} = \frac{z^2+z+1}{z^2+(1-d_G)z+1}$$
$$= \frac{z^2+z+1}{(1-\gamma z)(1-\gamma^{-1}z)} = (z^2+z+1)\sum_{n\geq 0}(\gamma z)^n \sum_{m\geq 0}(\gamma^{-1}z)^m,$$

where γ is the smallest positive root of $z^2+(1-d_G)z+1$. Therefore

$$|B_n \setminus B_{n-1}| = \gamma^n(3-\gamma^{-2n-2}-\gamma^{-2n}-\gamma^{-2n+2})/(1-\gamma^{-2})$$

for $n \geq 1$. Thus $\theta = \gamma$ exists and $\theta - 1 = \sqrt{d_G-3}(\sqrt{d_G-3}+\sqrt{d_G+1})/2$, which is easily verified to be larger than $\iota'_E(G)$. One may also verify from the lower bound of [3], Theorem 5.1, that if $d^\dagger - 2 \geq d \geq 5$, then $\inf_n |B_n \setminus B_{n-1}|/|B_n| > \iota_E(G)$.

Theorem 4.1 follows from applying the following identity to G and $G^\dagger$, then solving the resulting two equations using (26) and (27).

THEOREM 4.4. *For any planar regular graph G with regular dual, we have*

$$\beta(G) + \delta(G^\dagger) = 1.$$

PROOF. Note first that the constant $\iota'_E(G)$ is unchanged if, in its definition, we require K to be connected and simply connected when K is regarded as a union of closed faces of $G^\dagger$ in the plane. This is because filling in holes increases $|K|$ and decreases $|\partial_E K|$. Since G is regular, the same holds for $\beta(G)$ by (26). Likewise, the assumed regularity of $G^\dagger$ and (27) imply a comparable statement for $\delta(G^\dagger)$. In fact, we shall need a refinement of this idea for $\delta(G^\dagger)$. Namely, given a finite connected set K in $V(G^\dagger)$, regard each element of K as a face of G and let $K' \subset V$ be the set of vertices bounding these faces. Let $\widehat{K}$ be the set of all faces in $G^\dagger$ that lie in the interior of the outermost cycle formed by $E(K')$. Then again $|\widehat{K}| \geq |K|$ and $|\partial_E \widehat{K}| \leq |\partial_E K|$, so that $\delta(G^\dagger)$ can be approached arbitrarily closely by such sets $\widehat{K}$. Note that $|E^*(\widehat{K})| = |E((\widehat{K})')|$.

Now let $\varepsilon > 0$ and let K be a finite connected set in $V(G^\dagger)$ such that $|E^*(K)| > 1/\varepsilon$, $|K|/|E^*(K)| \geq \delta(G^\dagger) - \varepsilon$ and $|E(K')| = |E^*(K)|$, where K' is defined as above. Since the number of faces of the graph $G(K')$ is at least $|K|+1$, Euler's formula applied to the graph $G(K')$ gives

$$|K'|/|E(K')| + |K|/|E^*(K)| \leq 1 + 1/|E^*(K)| < 1 + \varepsilon. \tag{29}$$

Our choice of K then implies that

$$|K'|/|E(K')| + \delta(G^\dagger) \leq 1 + 2\varepsilon\,.$$

Since $G(K')$ is connected and $|K'| \to \infty$ when $\varepsilon \to 0$, it follows that $\beta(G) + \delta(G^\dagger) \leq 1$.

To prove that $\beta(G)+\delta(G^\dagger)\geq 1$, let $\varepsilon>0$. Let $K\subset V$ be connected and simply connected (when regarded as a union of closed faces of $G^\dagger$ in the plane) such that $|K|/|E(K)|\leq\beta(G)+\varepsilon$. Let K^f be the set of vertices in $G^\dagger$ corresponding to the faces of $G(K)$. Since $|E^*(K^f)|\leq|E(K)|$ and the number of faces of the graph $G(K)$ is precisely $|K^f|+1$, we have

$$\begin{aligned}|K|/|E(K)|+|K^f|/|E^*(K^f)|&\geq|K|/|E(K)|+|K^f|/|E(K)|\\&=1+1/|E(K)|\geq 1\end{aligned}$$

by Euler's formula applied to the graph $G(K)$. [In case K^f is empty, a comparable calculation shows that $|K|/|E(K)|\geq 1$.] In light of (28), it follows that

$$\begin{aligned}\beta(G)+\delta(G^\dagger)+\varepsilon&\geq\beta(G)+\varepsilon+|K^f|/|E^*(K^f)|\\&\geq|K|/|E(K)|+|K^f|/|E^*(K^f)|\geq 1.\end{aligned}$$

Since ε is arbitrary, the desired inequality follows. □

From (26) and (27), we see that $\beta(G)>\delta(G)$ when G is regular and $\iota'_E(G)>0$. Thus we obtain the following inequality.

COROLLARY 4.5. *If G is a planar regular graph with nonamenable regular dual, then*

$$\beta(G)+\beta(G^\dagger)>1.$$

The proof of Theorem 4.4 appears not to give any idea of which finite sets $K\subset V$ yield quotients $|\partial_E K|/|K|$ close to $\iota'_E(G)$. However, Peres has deduced the following from a closer examination of the proof. As in the proof of Theorem 4.4, we shall write K' for the set of vertices incident to the faces corresponding to K, for both $K\subset V$ and $K\subset V^\dagger$. Likewise, $\widehat{K}$ denotes the faces inside the outermost cycle of $E(K')$. According to the reasoning of the first paragraph of the proof of Theorem 4.4 and (29), we have

$$\begin{aligned}|(\widehat{K})'|/|E((\widehat{K})')|+|K|/|E^*(K)|&\leq|(\widehat{K})'|/|E((\widehat{K})')|+|\widehat{K}|/|E^*(\widehat{K})|\\&\leq 1+1/|E((\widehat{K})')|.\end{aligned}\tag{30}$$

PROPOSITION 4.6. *Let G be a planar regular graph with regular dual $G^\dagger$. Let $K_0\subset V$ be an arbitrary finite connected set and recursively define $L_n:=(\widehat{K}_n)'\subset V^\dagger$ and $K_{n+1}:=(\widehat{L}_n)'\subset V$. Then $|\partial_E K_n|/|K_n|\to\iota'_E(G)$ and $|\partial_E L_n|/|L_n|\to\iota'_E(G^\dagger)$.*

PROOF. The three amenable cases are trivial, so assume that G is nonamenable. Write

$$\kappa_n:=|\partial_E K_n|/|K_n|-\iota'_E(G)$$

and

$$\lambda_n:=|\partial_E L_n|/|L_n|-\iota'_E(G^\dagger).$$

Also write $d := d_G$, $d^\dagger := d_{G^\dagger}$, $\iota := \iota'_E(G)$ and $\iota^\dagger := \iota'_E(G^\dagger)$. We may rewrite (30) as

$$\frac{2}{d^\dagger - |\partial_E L_n|/|L_n|} + \frac{2}{d + |\partial_E K_n|/|K_n|} \le 1 + \frac{1}{|E(L_n)|}$$

or, again, as

$$\frac{2}{d^\dagger - \iota^\dagger - \lambda_n} + \frac{2}{d + \iota + \kappa_n} \le 1 + \frac{1}{|E(L_n)|} = \frac{2}{d^\dagger - \iota^\dagger} + \frac{2}{d + \iota} + \frac{1}{|E(L_n)|},$$

whence

$$\frac{2\lambda_n}{(d^\dagger - \iota^\dagger)(d^\dagger - \iota^\dagger - \lambda_n)} + \frac{2\kappa_n}{(d + \iota)(d + \iota + \kappa_n)} \le \frac{1}{|E(L_n)|}.$$

Therefore

$$\begin{aligned} 2\lambda_n &\le \frac{(d^\dagger - \iota^\dagger)(d^\dagger - \iota^\dagger - \lambda_n)}{(d + \iota)(d + \iota + \kappa_n)}(2\kappa_n) + \frac{(d^\dagger - \iota^\dagger)(d^\dagger - \iota^\dagger - \lambda_n)}{|E(L_n)|} \\ &\le \left(\frac{d^\dagger - \iota^\dagger}{d + \iota}\right)^2 2\kappa_n + \frac{(d^\dagger - \iota^\dagger)^2}{|E(L_n)|}. \end{aligned}$$

Similarly, we have

$$2\kappa_{n+1} \le \left(\frac{d - \iota}{d^\dagger + \iota^\dagger}\right)^2 2\lambda_n + \frac{(d - \iota)^2}{|E(K_{n+1})|}.$$

Putting these together, we obtain

$$2\kappa_{n+1} \le a(2\kappa_n) + b_n,$$

where

$$a := \left(\frac{(d - \iota)(d^\dagger - \iota^\dagger)}{(d + \iota)(d^\dagger + \iota^\dagger)}\right)^2$$

and

$$b_n := \left(\frac{(d - \iota)(d^\dagger - \iota^\dagger)}{d^\dagger + \iota^\dagger}\right)^2 \frac{1}{|E(L_n)|} + \frac{(d - \iota)^2}{|E(K_{n+1})|}.$$

Therefore

$$2\kappa_n \le 2\kappa_0 a^{n-1} + \sum_{j=0}^{n-2} a^j b_{n-j}.$$

Since $a < 1$ and $b_n \to 0$, we obtain $\kappa_n \to 0$. Hence $\lambda_n \to 0$, too. □

The following proposition relating the geometry of the graph to the behavior of the free random-cluster measure uses the ideas of [31] and [32].

PROPOSITION 4.7. *Let G be a graph with degrees bounded by d. Write $b := \log(p/(1-p))/\log q$ and $b^+ := \max\{b, 0\}$. If $b < \beta(G)$ and*

$$\log q > \frac{1 + \log(d-1)}{\beta(G) - b^+},$$

then $\mathsf{FRC}^G_{p,q}$-a.s. there is no infinite cluster.

REMARK 4.8. In this proposition, a better result is obtained by replacing $\beta(G)$ by the corresponding quantity that results when K is required to contain a fixed point o in the definition of $\beta(G)$. The same proof applies.

To prove Proposition 4.7, we shall use the following bound analogous to the well-known bound of Kesten [33] on site-connected clusters.

LEMMA 4.9. *Let G be a graph with degrees bounded by d. For any fixed $o \in V(G)$, let b_n be the number of connected subgraphs of G that contain o and have exactly n edges. Then $\limsup_{n\to\infty} b_n^{1/n} < e(d-1)$.*

PROOF. Let $b_{n,\ell}$ denote the number of connected subgraphs (V', E') of G such that $o \in V'$, $|E'| = n$ and $|E^*(V') \setminus E'| = \ell$. Note that, for such a subgraph,

$$\ell \le d|V'| - 2n \le d(n+1) - 2n = (d-2)n + d. \tag{31}$$

Let $p := 1/(d-1)$ and consider Bernoulli(p) bond percolation on G. Writing the fact that 1 is at least the probability that the cluster of o is finite and using (31), we obtain

$$1 \ge \sum_{n,\ell} b_{n,\ell}\, p^n (1-p)^\ell \ge \sum_n b_n p^n (1-p)^{(d-2)n+d}.$$

Therefore $\limsup_{n\to\infty} b_n^{1/n} \le 1/[p(1-p)^{d-2}]$. Putting in the chosen value of p gives the result. □

PROOF OF PROPOSITION 4.7. Because of (9), it suffices to prove the claim when $b \ge 0$. So assume that $b \ge 0$.

Let $o \in V(G_i)$ for all i. If ξ is a configuration, write $\xi(o)$ for the component of o determined by ξ. Suppose that $G' = (V(G'), E(G'))$ is a finite connected subgraph of G containing o. If ξ is a configuration in G_i such that $\xi(o) = G'$, then let ξ' be obtained from ξ by closing all edges in $E(G')$. Then $\|\xi'\| = \|\xi\| + |V(G')| - 1$, whence

$$\mathsf{RC}^{G,i}_{p,q}[\xi] = \left(\frac{p}{1-p}\right)^{|E(G')|} q^{-|V(G')|+1} \mathsf{RC}^{G,i}_{p,q}[\xi'].$$

Also, if $\xi_1 \neq \xi_2$ are such that $\xi_1(o) = \xi_2(o) = G'$, then $\xi_1' \neq \xi_2'$. Summing over all ξ such that $\xi(o) = G'$ yields

$$\mathsf{RC}_{p,q}^{G,i}[\xi(o) = G'] \leq \left(\frac{p}{1-p}\right)^{|E(G')|} q^{-|V(G')|+1}.$$

Now the right-hand side equals $q^{b|E(G')|-|V(G')|+1}$ by the definition of b. Choose $b' \in (b, \beta(G))$. Then, provided that $|V(G')|$ is sufficiently large, we have that the right-hand side is less than $q^{(b-b')|E(G')|+1}$. Therefore, for all large N, we have, by Lemma 4.9, that

$$\mathsf{RC}_{p,q}^{G,i}\bigl[\bigl|E\bigl(\xi(o)\bigr)\bigr| \geq N\bigr] \leq \sum_{n \geq N} \bigl(e(d-1)\bigr)^n q^{(b-b')n+1} < \infty$$

if $\log q > (1 + \log(d-1))/(b' - b)$. Therefore, for such q, this sum tends to 0 as $N \to \infty$, so that, given any $\varepsilon > 0$, there is some N_0 such that, for all $N \geq N_0$ and for all i, we have $\mathsf{RC}_{p,q}^{G,i}[|E(\xi(o))| \geq N] < \varepsilon$. Since the event $\{|E(\xi(o))| \geq N\}$ depends only on the edges within distance N of o, it follows that $\mathsf{FRC}_{p,q}^{G}[|E(\xi(o))| \geq N] < \varepsilon$. Since $\varepsilon > 0$ is arbitrary, we find that $\mathsf{FRC}_{p,q}^{G}[|E(\xi(o))| = \infty] = 0$. □

COROLLARY 4.10. *Let G be a planar quasi-transitive graph whose dual has degrees bounded by $d^\dagger$. Write $b := \log(p/(1-p))/\log q$. If $b > 1 - \beta(G^\dagger)$ and*

$$\log q > \frac{1 + \log(d^\dagger - 1)}{b \wedge 1 - 1 + \beta(G^\dagger)},$$

then $\mathsf{WRC}_{p,q}^{G}$-a.s. there is a unique infinite cluster.

PROOF. Let p' be as in (24). Then $p'/(1-p') = q(1-p)/p$. Let $b' := \log(p'/(1-p'))/\log q = 1 - b$. By our hypothesis, $b' < \beta(G^\dagger)$ and $\log q > (1 + \log(d^\dagger - 1))/(\beta(G^\dagger) - (b')^+)$, whence Proposition 4.7 applied to $G^\dagger$ shows that there is no infinite cluster $\mathsf{FRC}_{p',q}^{G^\dagger}$-a.s. Hence the conclusion follows from Proposition 3.5. □

Putting all this together, we arrive at our main result in this section.

THEOREM 4.11. *If G is a planar regular nonamenable graph of degree d with regular dual of degree $d^\dagger$, then $p_{\mathrm{c}}^{\mathrm{free}}(q) > p_{\mathrm{u}}^{\mathrm{wired}}(q)$ for*

$$\log q > \frac{\bigl(2 + \log\bigl((d-1)(d^\dagger - 1)\bigr)\bigr)(dd^\dagger - d - d^\dagger)}{\sqrt{(d-2)(d^\dagger - 2)(dd^\dagger - 2d - 2d^\dagger)}}.$$

PROOF. Let

$$b_0 := \frac{\bigl(1 + \log(d-1)\bigr)\bigl(1 - \beta(G^\dagger)\bigr) + \bigl(1 + \log(d^\dagger - 1)\bigr)\beta(G)}{\bigl(1 + \log(d-1)\bigr) + \bigl(1 + \log(d^\dagger - 1)\bigr)}.$$

Then $0 < 1 - \beta(G^\dagger) < b_0 < \beta(G) < 1$ because of Corollary 4.5. Furthermore, we have

$$\frac{1+\log(d-1)}{\beta(G)-b_0^+} = \frac{1+\log(d^\dagger-1)}{b_0 \wedge 1 - 1 + \beta(G^\dagger)}$$
$$= \frac{\big(2+\log\big((d-1)(d^\dagger-1)\big)\big)(dd^\dagger-d-d^\dagger)}{\sqrt{(d-2)(d^\dagger-2)(dd^\dagger-2d-2d^\dagger)}}$$

since

$$\beta(G) = \frac{d(d^\dagger-2)+\sqrt{(d-2)(d^\dagger-2)(dd^\dagger-2d-2d^\dagger)}}{2(dd^\dagger-d-d^\dagger)},$$

which follows from Theorem 4.1 and some calculation. Thus there is a positive-length interval of p for which b in Proposition 4.7 is close enough to b_0 that the hypotheses of both Proposition 4.7 and Corollary 4.10 are satisfied. This gives the result. □

REMARK 4.12. Even when $p_c^{\text{free}} = p_u^{\text{wired}}$, there is no infinite cluster $\mathsf{FRC}_{p,q}$-a.s. and a unique infinite cluster $\mathsf{WRC}_{p,q}$-a.s. for $p = p_c^{\text{free}} = p_u^{\text{wired}}$, in view of Theorem 3.1 and Corollary 3.7.

For comparison, we present the following bounds on when the opposite inequality $p_c^{\text{free}}(q) < p_u^{\text{wired}}(q)$ holds.

PROPOSITION 4.13. *If G is a planar regular nonamenable graph of degree d with regular dual of degree $d^\dagger$, then $p_c^{\text{free}}(q) < p_u^{\text{wired}}(q)$ for $q < dd^\dagger - 2d - 2d^\dagger$.*

For example, if $d = d^\dagger = 5$, then $p_c^{\text{free}} < p_u^{\text{wired}}$ if $q < 5$, while $p_c^{\text{free}} > p_u^{\text{wired}}$ if $q > (4e)^{2\sqrt{5}} = 43124^-$.

PROOF. We claim that $p_c^{\text{free}}(G,q) < p_u^{\text{wired}}(G,q)$ if

$$h\big(p_c(G)\big)h\big(p_c(G^\dagger)\big) < 1/q, \tag{32}$$

where h is defined as in (25). Indeed,

$$h\big(p_c^{\text{free}}(G,q)\big) \le qh\big(p_c(G)\big) \tag{33}$$

by (9) [applied with $p_1 = p$, $q_1 = 1$, $q_2 = q$ and p_2 chosen so that $h(p) = h(p_2)/q$] and

$$h\big(p_u^{\text{wired}}(G,q)\big) = q/h\big(p_c^{\text{free}}(G^\dagger,q)\big) \ge 1/h\big(p_c(G^\dagger)\big) \tag{34}$$

by Corollary 3.6 and (33) (applied to $G^\dagger$). Therefore, if (32) holds, then (33) and (34) give

$$h\big(p_c^{\text{free}}(G,q)\big) \le q h\big(p_c(G)\big) < 1/h\big(p_c(G^\dagger)\big) \le h\big(p_u^{\text{wired}}(G,q)\big),$$

which implies that $p_c^{\text{free}}(G,q) < p_u^{\text{wired}}(G,q)$.

Now $p_c(G) \le 1/(1+\iota_E(G))$ by [4]. Therefore (32) is implied by $\iota_E(G)\iota_E(G^\dagger) > q$. This is the same as the claimed range of q, as Theorem 4.1 and some calculation show. □

REMARK 4.14. Note that when $p_c^{\text{free}}(G) < p_u^{\text{wired}}(G)$ we also have $p_c^{\text{wired}}(G) < p_u^{\text{free}}(G)$, and thus we have an interval of p for which $\mathsf{FRC}_p \ne \mathsf{WRC}_p$ (see Proposition 3.8). For $q = 2$, the condition in Proposition 4.13 shows that this holds for $d^\dagger = 3$ when $d > 8$, for $d^\dagger = 4$ when $d > 5$ and for all $d^\dagger \ge 5$ when $d \ge 5$. This generalizes the main result in [46].

We end the section with some open questions.

QUESTION 4.15. Let G be a nonamenable quasi-transitive graph. Is the set of q for which $p_c^{\text{free}}(G,q) > p_u^{\text{wired}}(G,q)$ an interval? If G has only one end, is the set of such q nonempty?

QUESTION 4.16. If G is nonamenable and quasi-transitive, can there be any $q > 1$ such that $p_c^{\text{wired}}(G,q) = p_u^{\text{free}}(G,q)$ (so that all four critical values coincide)?

5. Robust phase transition. A classical question about the Potts model concerns when it exhibits a phase transition for given q, β and G. We say that a *phase transition* occurs when there is more than one Gibbs measure for the q-state Potts model on G with inverse temperature β. As noted in Section 3, this happens iff $\mathsf{WPt}^G_{q,\beta,r_1} \ne \mathsf{WPt}^G_{q,\beta,r_2}$ for $r_1 \ne r_2$. This is equivalent to the statement $\mathsf{WPt}^G_{q,\beta,r}(\omega(o) = r) > 1/r$ for any fixed vertex $o \in V$ and also to $\mathsf{WRC}^G_{p,q}(o \leftrightarrow \infty) > 0$, where $p := 1 - e^{-2\beta}$ and $\{o \leftrightarrow \infty\}$ is the event that o is contained in an infinite open cluster. Let $\{o \leftrightarrow \partial V_i\}$ be the event that o is connected to ∂V_i by a path of open edges in G_i (where G_i, V_i and E_i are as in Section 2). It follows that phase transition in the q-state Potts model with the given parameters is equivalent to $\inf_i \mathsf{WRC}^{G,i}_{p,q}(o \leftrightarrow \partial V_i) > 0$. Hence there exists a critical value β_c [given by $\beta_c = -\frac{1}{2}\log(1 - p_c^{\text{wired}})$] such that we have phase transition for $\beta > \beta_c$, but not for $\beta < \beta_c$.

Pemantle and Steif [39] introduced the stronger concept of robust phase transition. Although they considered mostly the Heisenberg model, they also have some results concerning robust phase transition in the Potts model. In order to define this notion, we need to generalize the Potts model slightly: When defining

$\mathsf{Pt}^{G_i}_{q,\beta}$, let us allow different interaction along different edges, that is, replace β with $\mathbf{B} := \{\beta_e\}_{e\in E_i}$. It is then straightforward to modify the measures $\mathsf{Pt}^{G_i}_{q,\mathbf{B}}$ to measures $\mathsf{FPt}^{G,i}_{q,\mathbf{B}}$ and $\mathsf{WPt}^{G,i}_{q,\mathbf{B}}$ in the same way as we did in Section 2 for the case $\mathbf{B} \equiv \beta$. Now, for $\varepsilon > 0$, define $\mathbf{B}^i_\varepsilon$ so that $B^i_\varepsilon(e)$ equals ε for all edges with one endpoint in ∂V_i and equals β for all other edges. We say that the q-state Potts model with inverse temperature β exhibits a *robust phase transition* if $\inf_i \mathsf{WPt}^{G,i}_{q,\mathbf{B}^i_\varepsilon,r}(\omega(o) = r) > 1/r$ for *all* $\varepsilon > 0$.

By making a corresponding extension of the random-cluster model, that is, by replacing p with $\mathbf{p} := \{p_e\}_{e\in E_i}$, we see that this is equivalent to

$$\inf_i \mathsf{WRC}^{G,i}_{\mathbf{p}^i_s,q}(o \leftrightarrow \partial V_i) > 0$$

for all $s > 0$, where $\mathbf{p}^i_s$ equals $p := 1 - e^{-2\beta}$ for edges that do not have an endpoint in ∂V_i and equals s for those that do. Pemantle and Steif showed that when G is a tree and $q \ge 3$, there is sometimes a phase transition but not a robust phase transition. In particular, they showed the following. On trees, the critical value $\beta_{\mathrm{c}}^{\mathrm{robust}}$ for robust phase transition is a strictly decreasing function of the branching number of the tree, but β_{c} is not. Consequently, if T_1 and T_2 are two trees with $\mathrm{br}(T_1) < \mathrm{br}(T_2)$ but where the q-state Potts model exhibits a phase transition on T_1 but not on T_2, then this happens for an interval of inverse temperatures on T_1. For instance, if G is taken to be the binary tree and $q \ge 3$, then there exists an $\varepsilon > 0$ such that there is a phase transition but not a robust phase transition when $e^{2\beta} - 1 \in (q - \varepsilon, q)$. See Theorems 1.13 and 1.14 of [39]. We show the following.

THEOREM 5.1. *Let G be an infinite regular nonamenable graph with degree d. Then there exists $q_0 < \infty$ such that, for $q \ge q_0$ and $e^{2\beta} - 1 \in [q^{2/(d+\iota'_E(G)/2)}, q^{2/(d-\iota'_E(G)/2)}]$, the q-state Potts model on G with inverse temperature β exhibits a phase transition but not a robust phase transition.*

PROOF. Fix i. From the definition of $\mathsf{WRC}^{G,i}_{\mathbf{p}^i_s,q}$, it is clear that we may, instead of regarding the vertices outside V_i as connected, regard them as contracted to a single vertex v_0. Now define a new graph H_i by adding an edge between v_0 and all vertices of V_i; that is, let $V(H_i) := V_i \cup \{v_0\}$ and $E(H_i) := E(V_i) \cup E_0$, where $E_0 := \{[v_0, v]; v \in V_i\}$. Let $\tilde{\mathbf{p}}$ be s for all edges of E_0 and p for all other edges. Then, by conditioning on $\mathsf{RC}^{H_i}_{\tilde{\mathbf{p}},q}(E_0)$ and using Holley's inequality, we see that

$$\mathsf{RC}^{H_i}_{\tilde{\mathbf{p}},q}\big(E^*(V_i)\big) \overset{\mathcal{D}}{\succcurlyeq} \mathsf{WRC}^{G,i}_{\mathbf{p}^i_s,q}. \tag{35}$$

Now the proof of [31], Theorem 1.2(a), shows precisely that, for q large enough, s small enough and β in the range indicated, $\inf_i \mathsf{RC}^{H_i}_{\tilde{\mathbf{p}},q}(A_i) = 0$, where A_i is the event that there is a path of open edges connecting o to ∂V_i without passing through v_0. [The proof is essentially the same as that of Proposition 4.7, but here one has to take the edges of E_0 into account. This is done by a simple application of Markov's inequality.] By (35), it follows that there is no robust phase transition in the corresponding Potts model. On the other hand, [31], Theorem 4.4(a), says that, for q large enough, a phase transition occurs for β in the range indicated. □

Let us now briefly consider the case when G is instead an amenable quasi-transitive graph. Then, as noted above, $\mathsf{FRC}_{p,q} = \mathsf{WRC}_{p,q}$ for all but at most countably many values of p. Therefore, if $\mathsf{WRC}_{p,q}(o \leftrightarrow \infty) > 0$, then $\mathsf{FRC}_{p',q}(o \leftrightarrow \infty) > 0$ for all $p' > p$. This strongly suggests that $\inf_i \mathsf{FRC}^{G,i}_{p',q}(o \leftrightarrow \partial V_i) > 0$, and since $\mathsf{FRC}^{G,i}_{p,q}$ is $\mathsf{WRC}^{G,i}_{\mathbf{p}^i_s,q}$ with $s = 0$, this would imply that the critical temperatures for phase transition and robust phase transition coincide. However, as $\mathsf{FRC}^{G,i}_{p,q}$ is increasing in i, it is possible to imagine a scenario where o is not connected to ∂V_i for any i but still connected to ∞ in the limit. This does not happen for the WRC measures on any graph ([1], proof of Theorem 2.3(c)), but is unknown for FRC.

QUESTION 5.2. If G is amenable and quasi-transitive, is the critical inverse temperature for robust phase transition β_c?

This question does not address the case $\beta = \beta_c$. For $G := \mathbf{Z}^d$, $d \geq 2$ and q large, it is well known that the Potts model at criticality ($\beta = \beta_c$) exhibits phase transition, whereas it was recently shown by van Enter [16] that (still at criticality) there is no robust phase transition.

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