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Inverse Ising inference, hyperuniformity, and absorbing states in the Manna model

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Using inverse Ising inference we show that the absorbing states of the one-dimensional Manna model can be described by an equilibrium model with an emergent interaction displaying short-ranged repulsion and long-ranged attraction. As the model approaches the critical point the interaction becomes purely repulsive, decaying as $r^{-\alpha}$ and we conjecture the exact value $\alpha = 1/2$, suggesting density fluctuations decay as $r^{-3/2}$. We present a simple Gaussian field theory for the long-distance behavior of critical absorbing states and discuss implications for the Manna universality class.

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I. INTRODUCTION

For a distribution of particles in a domain of dimension $d$, two extremes of order are uniform randomness and perfect crystalline structure. In the first case, the expected density of particles in regions of size $\ell$, $\langle \rho_c \rangle$, may be thought of as the average of $\sim \ell^d$ independent and identically distributed (iid) random variables, so that the density fluctuations behave as $\sigma^2(\rho_c) \sim \ell^{-d}$. For a perfect crystal the number of particles in a region $R$ is proportional to the number of unit cells in $R$ with variation only in how $\partial R$ (comparable to $\partial \ell^d$) intersects the crystal lattice. It follows for reasonable choices of $R$, such as spheres of radius $\ell$, that the density fluctuations behave as $\sigma^2(\rho_c) \sim \ell^{-d\lambda}$. Between these two extremes lie classes of systems, which, while disordered, display suppressed density fluctuations where $\sigma^2(\rho_c) \sim \ell^{-d\lambda}$, $d < \lambda < d + 1$; such systems are said to exhibit disordered hyperuniformity [1,2]. In Ref. [3] a variety of critical absorbing states in nonequilibrium models were shown to have suppressed, hyperuniform density fluctuations, with similar findings in other studies [4,5].

Because a distribution of absorbing states has no intrinsic dynamics, it is completely characterized by the equilibrium distribution of some unknown (and potentially unphysical) Hamiltonian. The goal of this paper is to determine the form of the equilibrium model corresponding to the critical point of an absorbing phase transition in the Manna universality class. Using inverse Ising inference we numerically estimate a model that reproduces the suppressed density fluctuations found in absorbing states as the density $\rho$ approaches the critical density $\rho_c$. Below $\rho_c$, we find an effective potential exhibiting short-range repulsion and long-range attraction decaying as $r^{-\beta}$, with a minimum located at $x_{\text{min}}(\rho_c - \rho)$. As $\rho_c - \rho \to 0$, $x_{\text{min}} \sim (\rho_c - \rho)^{-\gamma}$, where $\gamma \approx 1.4$.

At $\rho_c$, the interaction is purely repulsive, decaying as $r^{-\alpha}$. Based on our numerical results, we conjecture that $\alpha$ takes the exact value $1/2$. We present a short analysis of the inferred equilibrium model at the critical point. While numerical simulations reproduce the exponent $\lambda \approx 1.425$ found in Ref. [3], the model may also be studied analytically, where the long-range behavior is Gaussian, and one finds $\lambda = 3/2$. Taken together, the results suggest that the discrepancy may be a finite-size effect, with $3/2$ the true value. This supports the hypothesis [6] that the Manna universality class (believed to be conserved directed percolation [7]) is related to theories of interface depinning in quenched disorder, for which one would expect $\lambda = 3/2$ [4].

II. THE MANNA MODEL AND INVERSE ISING INFERENCE

We begin with the one-dimensional (1D) Manna model with carrying capacity one [8]. The model is defined on a one-dimensional periodic lattice of size $L$ with each lattice site having occupancy $n_i \in \mathbb{N}_0$. Sites with $n_i$ greater than the carrying capacity are deemed active. Active sites update by distributing all particles among their nearest neighbors. In this study these updates are done sequentially with active sites chosen at random, though the model may be defined with parallel updates with no consequence for the critical behavior [9]. The model thus defined has two parameters, the density $\rho$ and lattice size, $L$. As $L \to \infty$ the model exhibits an absorbing phase transition [10]. For $\rho > \rho_c \approx 0.892$ [9,11,12] the system is in the active state, and the density of active sites approaches a nonzero constant. For $\rho < \rho_c$, the system eventually reaches an absorbing state, with zero active sites. The Manna model with carrying capacity one was not studied in Ref. [3], so we first establish that the absorbing states exhibit disordered hyperuniformity as $\rho \to \rho_c$. The results are shown in Fig. 1, and the data for $\rho = 0.8921$ give $\lambda = 1.424 \pm 0.016$. This is consistent with the value $\lambda = 1.425 \pm 0.025$ found for other nonequilibrium one-dimensional systems [3].

Because the set of absorbing states has no dynamics associated to it, it is completely characterized by the properties of a corresponding equilibrium system. For a given distribution of initial conditions $I$, lattice size $L$, and density $\rho$ the model defines a probability distribution

$$P_{L,\rho,I}(\{n_i\})$$

(1)
We treat this problem numerically, where it falls under the domain of inverse Ising inference [15,16]. We take numerically generated configurations and infer the effective interaction model (3). We impose a maximum range, $r$, on the coupling coefficients, which we infer, so that $J_r(x) = 0$ for $x > r$. In the work presented here $r \ll L$, the lattice size, so we assume any finite-size effects coming from the lattice are negligible compared to the noise in the inference and to finite-size effects from $r$. To estimate the chemical potential $\mu_r$ and the vector of interactions $\mathbf{J}$, we found pseudolikelihood maximization (ordered logistic regression) to be effective [16]. Given a sample $S$ with configuration $\{n_i,s\}$ of carrying capacity $C$, and a site $j$, we form the conditional probability

$$P_{j.s} = P(n_{j,s}|\{n_i,s\} \setminus j,s) = \frac{e^{\mathbf{J}_s \cdot \mathbf{n}_s}}{\sum_{s=0}^{2^r} e^{k}},$$

where $z = \exp(-H_{j.s})$ and

$$H_{j.s} = \mu_r + \sum_{i \neq j} J_r(|i - j|) n_{i,s}$$

is the contribution to the energy from site $j$ in sample $S$. The estimates ($\hat{\mu}_r, \hat{\mathbf{J}}$) are found by maximizing the pseudo-log-likelihood

$$L = \sum_{s,i} \log P_{s,i},$$

where the sum is over all samples, $S$, and sites, $i$. One can show that if the data are generated by an equilibrium model with two-body interactions, then this procedure gives a consistent estimator of the true interactions [16]. We used BFGS pseudo-Newtonian optimization to maximize (6). To ensure stability of the algorithm for large $r$, inferred couplings for $\hat{r} < r$ were used as initial conditions to estimate ($\hat{\mu}_r, \hat{\mathbf{J}}$). For this process to be well defined, the estimates of $\mathbf{J}$ should converge as $r$ gets large (note that $\hat{\mu}_r$ need not converge for reasons discussed below) and this is indeed the case (see Fig. 3).

### III. Numerical Results for Inverse Ising Inference

Results for the inferred interaction potentials for $\rho$ close to $\rho_c$ are shown in Fig. 2 (similar results were obtained for other carrying capacities). For $\rho < \rho_c$, the interaction potential displays short-range repulsion and long-range attraction with the minimum of the interaction located at some value $x_{\text{min}}(\rho)$. As $\rho \to \rho_c$, $x_{\text{min}} \to \infty$ so that the interaction is purely repulsive at the critical point, consistent with the negative correlation functions that are typical of hyperuniform systems [1]. We note also that other nonequilibrium systems with local dynamics can lead to effective long-range equilibrium interactions [17].

By construction, the inferred potentials reproduce the observed correlations in the absorbing states (see Fig. 5), and it is natural to ask which properties of the Manna model’s absorbing states emerge from the statistical mechanics of the inferred equilibrium system, and which are encoded into the parameters of the potentials. A possible example of the latter

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1}
\caption{Density fluctuations, $\sigma^2(\rho_c)$ as a function of density $\rho$ and window size $\ell$ for the one-dimensional Manna model with carrying capacity one. Below $\rho_c$, $\sigma^2(\rho_c) \sim \ell^{-k}$ for small $\ell$ and $\sim \ell^{-1}$ for large $\ell$. As $\rho \to \rho_c$, the crossover no longer occurs. Data from absorbing states on lattices of size $L = 10^5$. Sample size $N = 100$ except for $\rho = 0.8919$ and $\rho = 0.8921$ where $N = 40$. The data for $\rho = 0.8921$ gives $z = 1.424 \pm 0.016$. Note that for a given $\ell$, $\sigma^2(\rho_c)$ is a decreasing function of $\rho$.}
\end{figure}
is given by $x_{\text{min}}(\rho)$. As $\rho \to \rho_c$ we expect a scaling
\[ x_{\text{min}}(\rho) \sim (\rho_c - \rho)^{-a}. \] (7)

One may expect $x_{\text{min}} \propto \xi_{\text{s}}$, where $\xi_{\text{s}}$ is the crossover distance in the density fluctuations so that $a$ should be equal to $\nu - \nu_c = 1.347 \pm 0.091$, which controls the divergence of the active site-active site correlation length the in active state [3,11]. Computing $x_{\text{min}}$ for the inferred potentials, we estimate $a = 1.4 \pm 0.1$, consistent with the value of $\nu - \nu_c$. We can also study the attractive tail for $\rho < \rho_c$, however, the noise inherent in the inference process precludes a precise analysis. The data suggest that the tail decays as $-B x^{-\nu}$, where both $B$ and $C$ are functions of $\rho_c - \rho$. We estimate $B \sim (\rho_c - \rho)^{\gamma}$, $c = 1.7 \pm 0.3$, and $C \sim (\rho_c - \rho)^{\gamma}$, $b = 0.53 \pm 0.10$, with proportionality constant such that $C = 1.46 \pm 0.04$ for $\rho = 0.85$.

We now turn to the purely repulsive behavior at $\rho_c$, where we expect the model to describe the universal behavior of the nonequilibrium critical point. We note here that the inference process does not reproduce the distribution of absorbing states of the Manna model, just their correlations, so that only at large length scales do we expect their behaviors to match precisely. The required correlations cannot occur with short-range interactions [3], and the interaction potential must satisfy (in one dimension)
\[ \lim_{x \to \infty} \int_{-\infty}^{\infty} J(i) = \infty. \] (8)

If this does not hold then the system is additive and density fluctuations will typically scale asymptotically as $\ell^{-1}$. We discuss some of the subtleties associated with this long-range interaction below.

The inference procedure is noisy [18] at long ranges, making direct estimation of the long-range behavior difficult.

Instead, we analyze the behavior of the chemical potential. In order for the equilibrium model to be well defined in the thermodynamic limit, the energy difference upon adding a particle to a configuration with the equilibrium density should be finite,
\[ |H(n_j = 1, \{n_{ij}\}) - H(n_j = 0, \{n_{ij}\})| < \infty. \] (9)

If we assume an infinite chemical potential of the form $\mu = v \sum J(i)$, this condition becomes
\[ |\Delta H| = \left| \sum_{i=1}^{\infty} J(i) (n_{j+i} + n_{j-i} - v) \right| < \infty. \] (10)

For an interaction satisfying (8), $\Delta H = +\infty$ if $2\rho > v$ and $\Delta H = -\infty$ if $2\rho < v$. It follows that configurations with support in the equilibrium distribution of $H$ must have $2\rho = v$, which is a necessary (but not sufficient) condition for (10) to hold; the infinite chemical potential balances the strength of the long-ranged repulsive interaction giving a nonzero equilibrium density.

This allows us to infer the long-range nature of $J(x)$. Consider the estimated values $(\hat{\mu}_r, \hat{J})$. If we assume for large sample number, that as $r \to \infty$ the estimates of $\hat{J}$ converge to $J$ and that $J(x) \sim x^{-\alpha}$ then the asymptotic relation
\[ \hat{\mu}_r \sim r^{1-\alpha}. \] (11)

should hold as $r$ gets large. Since the inferred interaction has some short-range behavior that is not a power law, we add an additional constant and fit the inferred chemical potentials to the form $\mu(r) = \mu_0 + B r^C$, shown in Fig. 3, along with data for $\mu(r)$. We find $C = 0.499 \pm 0.016$. Given the strength of this relationship, we conjecture that the true value for the exponent $\alpha$ is exactly 1/2. This analysis permits the consistency check:
\[ \hat{\rho} := \frac{1}{2} \lim_{r \to \infty} \int_{-\infty}^{r} \hat{J}(i) = \rho. \] (12)

$\hat{\rho}$ may be estimated and compared with the known value of $\rho$. We find for $r = 4, 000$ and $\rho = 0.8921$, $\hat{\rho} = 0.90$. 

![FIG. 2. Inferred interaction potentials $\hat{J}(x)$ for the one-dimensional Manna model with varying values of $\rho \in [0.85, 0.8921]$, below $\rho_c \approx 0.8921$, displaying short-range repulsion and long-range attraction. As $\rho \to \rho_c$ the minimum of the potential tends to $\infty$ and the interaction becomes purely repulsive at $\rho_c$ (see Fig. 4). Data shown are from inferred potentials with maximum range $r = 1000$. Plots obtained using 100 samples of size $10^5$ for each value of $\rho$ with a range $r = 250$. Note that, as shown in the plot, $J(x)$ is a monotonically increasing function of $\rho$ for small $x$ ($< 8$).](image1.png)

![FIG. 3. A fit of $\hat{\mu}$ to the form $A + Br^C$. Note that $\hat{\mu}_r - A$ is shown on the vertical axis. We find $C = 0.499 \pm 0.016$. Instead, we analyze the behavior of the chemical potential. In order for the equilibrium model to be well defined in the thermodynamic limit, the energy difference upon adding a particle to a configuration with the equilibrium density should be finite,](image2.png)
occur here, the strength of the nonintegrable interactions locks the ground state to a simple functional form. As discussed above, the ground state of the model may be effectively computed, however, to ensure that the ground-state density is known, we use the algorithm given by Hubbard [19]. As an example, for \( r = 1/n \), the ground state contains alternating unoccupied sites with a per site energy of

\[
-H = \frac{1}{2} \sum_{ij} (n_i - \rho) J_{ij} (n_j - \rho) = \frac{1}{2} \sum_{ij} \sigma_i J_{ij} \sigma_j, \tag{13}
\]

where \( J_{ij} = J(|i - j|) = J_0 |i - j|^{-1/2} \), \( J(0) = 0 \). As established above, the long-range nature of the interactions fixes the density of the system to be equal to \( \rho \), and the theory is defined entirely in terms of the fluctuations \( \sigma_i = n_i - \rho \). It is important to note that (13) is not the same as the inferred model, shown in Fig. 4, where there is a short-range deviation from power-law behavior, which we do not include in (13).

As a system with repulsive convex interactions the ground state of the system can be calculated exactly for a given density \( \rho \), using the algorithm given by Hubbard [19]. As an example, for \( r = 1/n \), the ground state contains alternating unoccupied sites with a per site energy of

\[
\frac{J_0}{n^2} (\sqrt{n} - 1) \chi \left( \frac{1}{2} \right). \tag{14}
\]

Despite the nonintegrability of \( 1/\sqrt{r} \) interaction (8) the ground state of the system is extensive (a similar observation has been made in the case of frustrated systems [20]). Ultimately in this case, extensivity of the ground state is achieved via the infinite chemical potential, which should be set to scale as \( L^{3/2} \) for a finite system. The devil’s staircase phenomena found for the antiferromagnetic Ising model [21] does not occur here, the strength of the nonintegrable interactions locks the density of the system to \( \rho \).

We first investigate (13) numerically. We simulate the model in the canonical ensemble using standard Monte Carlo methods, the long-range interactions set the density equal to

\[
\hat{J}_r(x) \sim x^{-1/2}.
\]

IV. ANALYSIS OF THE EQUILIBRIUM MODEL

Given this conjecture, we are motivated to explore the equilibrium model with \( 1/\sqrt{r} \) interactions so defined. As discussed below, the ground state of the model may be effectively computed, however, to ensure that the ground-state energy is bounded from below, we add a constant term to the Hamiltonian bringing it to the form

\[
H = \frac{1}{2} \sum_{ij} (n_i - \rho) J_{ij} (n_j - \rho) = \frac{1}{2} \sum_{ij} \sigma_i J_{ij} \sigma_j, \tag{13}
\]

where \( J_{ij} = J(|i - j|) = J_0 |i - j|^{-1/2} \), \( J(0) = 0 \). As established above, the long-range nature of the interactions fixes the density of the system to be equal to \( \rho \), and the theory is defined entirely in terms of the fluctuations \( \sigma_i = n_i - \rho \). It is important to note that (13) is not the same as the inferred model, shown in Fig. 4, where there is a short-range deviation from power-law behavior, which we do not include in (13).

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\[
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Despite the nonintegrability of \( 1/\sqrt{r} \) interaction (8) the ground state of the system is extensive (a similar observation has been made in the case of frustrated systems [20]). Ultimately in this case, extensivity of the ground state is achieved via the infinite chemical potential, which should be set to scale as \( L^{3/2} \) for a finite system. The devil’s staircase phenomena found for the antiferromagnetic Ising model [21] does not occur here, the strength of the nonintegrable interactions locks the density of the system to \( \rho \).

We first investigate (13) numerically. We simulate the model in the canonical ensemble using standard Monte Carlo methods, the long-range interactions set the density equal to

\[
\hat{J}_r(x) \sim x^{-1/2}.
\]
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FIG. 6. Skewness and excess kurtosis of $\rho_\ell$ for the equilibrium model (13) and the Manna model (denoted by eq and m respectively). For $\ell \lesssim 2^{1/2} \sim L/20$, the moments decay to zero suggesting Gaussian behavior at large distances, supported by more comprehensive statistical tests (Shapiro-Wilks and Anderson-Darling, not shown). Beyond this length scale, we see finite-size effects in the fourth moment. Uncertainty is $2\sigma$. Manna data $L=10^3$, $N=40$, $\rho=0.8921$, equilibrium data, $L=10^5$, $N=600$, $\rho=0.8921$, $J_0=0.2$.

scale-invariant Gaussian theory

$$H = \int_{BZ} \frac{1}{|k|^{1/2}} |\phi(k)|^2 dk,$$

(18)

describing the long-distance behavior of critical absorbing states in the Manna universality class, for which elementary scaling arguments give $\lambda = 3/2$. We therefore conclude $\lambda = 3/2$ in (13).

Now we must reconcile the numerical value of $\lambda \approx 1.43$ with the analytical value of $\lambda = 3/2$ for the equilibrium model. From (18), we expect $\rho_\ell$ to be scale invariant on large length scales, so that its standardized moments are constant, and Gaussian. Figure 6 shows skewness and excess kurtosis of $\rho_\ell$ for both the equilibrium model as well as Manna model. For the system sizes studied, when $\ell \lesssim L/20$ this is indeed the case, and the behavior of $\rho_\ell$ is Gaussian for both the equilibrium and Manna models, suggesting (18) is accurate (this is confirmed by more robust statistical tests). This no longer holds as $\ell \gtrsim L/20$, where finite-size effects become relevant. This can also be seen in the density fluctuations, which show clear finite-size effects for $\ell \gtrsim L/10$. While density fluctuations are suppressed on length scales $\sim L/2$ for any periodic system, the long-range interactions of (13) increase the magnitude of this effect. We note that at fixed system size, simulations of (13) at other parameter values given values of $\lambda$ depending on $J_0$ and $\rho$, tending to $3/2$ as $J_0$ gets large and $\rho \to 1/2$, so that the strength of the finite-size effects depend on both $J_0$ and $\rho$.

Returning to the Manna model, the $-1/2$ interaction obtained by the inverse Ising inference process is well supported, evident even for small ranges of inferred interactions. If we accept that (13) reproduces the long-distance behavior of the Manna model, as it must, then we have $\lambda = 3/2$ for the Manna model. The conclusion is then that the value $\lambda \approx 1.424$, and other similar numerical values, are due to finite-size effects, which can be large in sandpile models [4]. It has been proposed [6] that conserved directed percolation [23,24] (believed to describe the Manna model [7]) is related to the quenched Edwards-Wilkinson model [25]. If this is the case, then one would expect $\lambda = 3/2$, as has been found for the Oslo model [4]. From this perspective then, one may interpret our results as evidence for the hypothesis of Ref. [6]. Finally, we note that an extension to higher dimensions, as well as a derivation of the $-1/2$ exponent would constitute interesting future directions.

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[18] It is potentially viable to use some form of regularization here, however, it was deemed unnecessary for our purposes.
[22] $J_0 = 0.3$ is slightly lower than the value $J_0 \approx 0.35$ found by the inference process.