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Multidimensional Central and Local Limit Theorems

for the Phase Separation Line in the

Two-Dimensional Ising Model

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§1. The Two-Dimensional Ising Model

Let \mathbb{Z}^2 be the square lattice and L be its dual lattice; *i.e.*

$$\mathbb{Z}^2 \equiv \{(x_1, x_2); x_1 \text{ and } x_2 \text{ are integers}\},$$

$$L \equiv \{(x_1, x_2) + (\frac{1}{2}, \frac{1}{2}); (x_1, x_2) \in \mathbb{Z}^2\}.$$

We consider \mathbb{Z}^2 and L also as graphs. Let $\Omega \equiv \{-1, +1\}^L$ be the space of possible spin configurations on L . For each positive integer N , we define a square box V_N by

$$V_N \equiv \{(x_1, x_2) + (\frac{1}{2}, \frac{1}{2}); (x_1, x_2) \in \mathbb{Z}^2, 0 \leq x_1 \leq N-1, -[\frac{N}{2}] \leq x_2 \leq [\frac{N-1}{2}]\},$$

where $[u]$ is the largest integer smaller than u . For given

$\omega \in \Omega$ and $\beta > 0$, the finite Gibbs state on $\Omega_N \equiv \{-1, +1\}^{V_N}$ with boundary condition ω , inverse temperature β (in the absence of the exterior magnetic field) is given by

$$P_N^\omega(\eta) = Z_N(\omega)^{-1} \exp\{-\beta U_N(\eta; \omega)\} \quad \eta \in \Omega_N$$

where $Z_N(\omega) \equiv \sum_{\eta' \in \Omega_N} \exp\{-\beta U_N(\eta'; \omega)\}$, and

$$U_N(\eta; \omega) \equiv - \sum_{x, y \in V_N}^* \eta(x)\eta(y) - \sum_{\substack{x \in V_N \\ y \in \partial V_N}}^* \eta(x)\omega(y),$$

where the summation $\sum_{x \in A, y \in B}^*$ is taken over all pairs (x, y)

such that (i) x and y are nearest neighbours in L , and

(ii) $x \in A$ and $y \in B$. From now on, we fix the boundary

condition ω as

$$\omega((x_1, x_2) + (\frac{1}{2}, \frac{1}{2})) = \begin{cases} +1 & \text{if } x_2 \geq 0 \\ -1 & \text{if } x_2 < 0, \end{cases}$$

and we write simply P_N instead of P_N^ω .

§2. The Phase Separation Line

Let us fix $N > 0$ arbitrarily. Define

$$\tilde{V}_N \equiv \{(x_1, x_2) \in \mathbb{Z}^2; 0 \leq x_1 \leq N, -[\frac{N+1}{2}] \leq x_2 \leq [\frac{N+1}{2}]\}.$$

We can regard \tilde{V}_N as a subgraph of \mathbb{Z}^2 . We call a segment of length one connecting two points which are nearest neighbours in \mathbb{Z}^2 (or in L) by "a bond in \mathbb{Z}^2 (or in L)". Then for each $\eta \in \Omega_N$, we can define a subgraph $C_N(\eta)$ of \tilde{V}_N in the following way. A bond in \mathbb{Z}^2 belongs to $C_N(\eta)$ if and only if it crosses a bond in L connecting two points $x, y \in L$ such that $\eta(x)\eta(y) = -1$ (or $\eta(x)\omega(y) = -1$). $C_N(\eta)$ consists of some connected components, and each vertex of $C_N(\eta)$ belongs to two of four bonds of $C_N(\eta)$ unless the vertex is $A = (0, 0)$ or $B = (N, 0)$. It is easy to see that the connected component of $C_N(\eta)$ containing A also contains B . We denote this component by $\lambda_N(\eta)$, and call it by "the phase separation line". Let $\Lambda_N \equiv \{\lambda_N(\eta) : \eta \in \Omega_N\}$, and $S \equiv \{\gamma; \text{subgraph of } \mathbb{Z}^2 \text{ such that (i) the length } |\gamma| \text{ is finite, and (ii) each vertex of } \gamma \text{ belongs to two or four bonds of } \gamma\}$.

Theorem (Gallavotti)

There exists a function $\varphi : \mathcal{N} = \bigoplus_{n=0}^{\infty} S^n \rightarrow \mathbb{R}$ such that

(i) φ is symmetric, (ii) $\sum_{\substack{\Gamma \in \mathcal{N} \\ \Gamma \ni 0}} |\varphi(\Gamma)| < +\infty$ and (iii) for each

$\lambda \in \Lambda_N$,

$$P_N(\{\eta \in \Omega_N; \lambda_N(\eta) = \lambda\}) = \exp\{-2\beta|\lambda| - \sum_{\substack{\Gamma \in \mathcal{N} \\ \Gamma \cap \lambda \neq \emptyset \\ \Gamma \subset V_N}} \varphi(\Gamma)\} / \sum_{\lambda' \in \Lambda_N} \exp\{-2\beta|\lambda'| - \sum_{\substack{\Gamma \in \mathcal{N} \\ \Gamma \cap \lambda' \neq \emptyset \\ \Gamma \subset \tilde{V}_N}} \varphi(\Gamma)\}.$$

We denote the left hand side of the above equality simply by $P_N(\lambda)$.

Thus we are given a sequence of probability spaces (Λ_N, P_N) .

To state our result, we need some notations. For each $\lambda \in \Lambda_N$, $0 \leq \ell \leq N$, let $\bar{X}_N(\ell)$ and $\underline{X}_N(\ell)$ be $\bar{X}_N(\ell) \equiv \max\{k; (k, \ell) \in \lambda\}$, $\underline{X}_N(\ell) \equiv \min\{k; (k, \ell) \in \lambda\}$.

Theorem 1.

Let an integer $k \geq 1$, and $0 < t_1 < t_2 < \dots < t_k < 1$ and the numbers $-\infty < T_j < T'_j < \infty$, $j = 1, 2, \dots, k$ be given arbitrarily. Let $a_j^{(N)} \equiv [t_j \cdot N]$ $j = 1, 2, \dots, k$, where $[u]$ is the largest integer smaller than u . Then,

$$\begin{aligned} & \lim_{N \rightarrow \infty} P_N \left(\bigcap_{j=1}^k \left\{ T_j \leq \frac{\bar{X}_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq T'_j \right\} \right) \\ &= \lim_{N \rightarrow \infty} P_N \left(\bigcap_{j=1}^k \left\{ T_j \leq \frac{\underline{X}_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq \frac{\bar{X}_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq T'_j \right\} \right) \\ &= P_0^1; 0^0 (X_{t_j} \in [T_j, T'_j], j = 1, 2, \dots, k) \end{aligned}$$

where $\sigma = \sigma(\beta) > 0$ is a constant depending only on $\beta > 0$ and $\{(X_t)\}_{0 \leq t \leq 1, P_0^1; 0^0}$ is a one-dimensional Brownian Bridge such that $P_0^1; 0^0(X_0 = X_1 = 0) = 1$.

Remark Gallavotti has proved the above theorem in the case when $k = 1$ in [2], and it is announced that Cammarota has proved it for general $k \geq 1$, but we have got nothing in print yet.

§3. An Auxiliary Ensemble and the Central Limit Theorem

In order to prove Theorem 1, we need another sequence of probability spaces $(\hat{\Lambda}_N, \hat{P}_N)$. Let $I_N \equiv \{(x_1, x_2) \in \mathbb{Z}^2; 0 \leq x_1 \leq N\}$, and $\hat{\Lambda}_N \equiv \{\text{connected subgraph } \lambda \text{ of } I_N \text{ such that (i) } |\lambda| < +\infty, \text{ (ii) } \lambda \ni A, \text{ (iii) there exists a point } B' \text{ in } \{(N, \ell): \ell \in \mathbb{Z}\}\}$

such that each vertex of λ belongs to two or four bonds of λ unless it is A or B' , and A and B' belong to one or three bonds of λ . For each $\lambda \in \hat{\Lambda}_N$, we define

$$\hat{P}_N(\lambda) \equiv \exp\{-2\beta|\lambda| - \sum_{\substack{\Gamma \in \mathcal{N} \\ \Gamma \subset I_N \\ \Gamma \cap \lambda \neq \emptyset}} \varphi(\Gamma)\} / \sum_{\tilde{\lambda} \in \hat{\Lambda}_N} \exp\{-2\beta|\tilde{\lambda}| - \sum_{\substack{\Gamma \in \mathcal{N} \\ \Gamma \subset I_N \\ \Gamma \cap \tilde{\lambda} \neq \emptyset}} \varphi(\Gamma)\}.$$

Then, Gallavotti has shown that for every $A_N \subset \Lambda_N$,

$$P_N(A_N) = \hat{P}_N(A_N | \tilde{\Lambda}_N) + o\left(\frac{1}{N^{\frac{1}{2}}}\right) \quad \text{as } N \rightarrow \infty \quad \forall \lambda \in \Lambda_N,$$

where $\tilde{\Lambda}_N \equiv \{\lambda \in \hat{\Lambda}_N; B' = B\}$.

Hence we only have to investigate the probability space $(\hat{\Lambda}_N, \hat{P}_N)$. we obtain the following theorem first, which is much easier to prove than Theorem 1.

Theorem 2.

For each integer $k \geq 1$, $0 = t_0 < t_1 < \dots < t_k < t_{k+1} = 1$ and $-\infty < T_j < T'_j < +\infty$, $j = 1, 2, \dots, k+1$, we have

$$\begin{aligned} & \lim_{N \rightarrow \infty} \hat{P}_N \left(\bigcap_{j=1}^{k+1} \left\{ T_j \leq \frac{\bar{X}_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq T'_j \right\} \right) \\ &= \lim_{N \rightarrow \infty} \hat{P}_N \left(\bigcap_{j=1}^{k+1} \left\{ T_j \leq \frac{X_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq \frac{X_N(a_j^{(N)})}{\sigma\sqrt{N}} \leq T'_j \right\} \right) \\ &= P_0 \left(X_{t_j} \in [T_j, T'_j], j = 1, 2, \dots, k+1 \right), \end{aligned}$$

where $(\{X_t\}, P_0)$ is a one-dimensional Brownian Motion starting at 0.

References

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