SURVIVAL AND COEXISTENCE IN INTERACTING PARTICLE SYSTEMS

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Abstract. A fifteen year old technique for proving survival of the basic one dimensional contact process is extended in order to obtain improved upper bounds for contact like processes. Comparison techniques are described which can be combined with these survival results to determine exactly which threshold voter models coexist. The paper ends with a bibliography of most of the papers written about interacting particle systems since the author's book on this subject appeared in 1985.

Key words: Interacting particle system, contact process, survival, voter model.

1. Survival of Contact-Like Processes

A proof of survival for the basic one dimensional contact process was given by Holley and Liggett in 1978 (see Section 1 of Chapter VI of Liggett (1985)). To begin the discussion of extensions of this technique, consider the following question: Does the (nontrivial) invariant measure of the basic one dimensional contact process have the strong positive correlations property? We need to define the terms which appear in this question.

The basic one dimensional contact process is the Markov process η_t on $\{0,1\}^{\mathbb{Z}}$ in which $1 \to 0$ at rate one and $0 \to 1$ at rate $\lambda \times$ (# neighbors which are 1). The distribution of the process at time t when the initial distribution is μ will be denoted by $\mu S(t)$. An invariant measure (i.e., one for which $\mu S(t) = \mu\ \forall t \geq 0$) is nontrivial if it is not the pointmass on the zero configuration. As is well known, there is a critical value λ_c so that the process survives (i.e., has a nontrivial invariant measure) if $\lambda > \lambda_c$ and dies out if $\lambda \leq \lambda_c$. The fact that the critical process dies out is rather recent — see Bezuidenhout and Grimmett (1990). Until recently, the best bounds on λ_c were $1.539 < \lambda_c < 2$. More on this will be said later.

A probability measure μ on $\{0,1\}^{\mathbb{Z}}$ is said to have the positive correlations property if

$$\int fg\,d\mu \geq \int f\,d\mu \int g\,d\mu$$

for all bounded increasing functions f and g. This property plays an important role in both statistical mechanics and interacting particle systems. We will say that μ

*Preparation of this paper was supported in part by NSF Grant 91-00725.

has the strong positive correlations property if the conditional measure

$$\mu(\cdot \mid \eta(x_1) = \epsilon_1, \ldots, \eta(x_n) = \epsilon_n)$$

has the positive correlations property for every n and every choice of $\epsilon_1, \ldots, \epsilon_n$.

A theorem due to Harris (Theorem 2.14 in Liggett (1985)) guarantees that for a large class of processes (including the contact process),

$$\mu \text{ has positive correlations } \implies \mu S(t) \text{ has positive correlations } \forall t \geq 0.$$

It follows (for $\lambda > \lambda_c$) that the nontrivial invariant measure of the contact process (which is the limit of $\delta_1 S(t)$) has positive correlations. This observation motivates the question raised above. One can strengthen the question by asking whether there is a version of Harris' theorem for the strong positive correlations property. Perhaps surprisingly, we will now answer our question in the negative. To do so, let μ be any translation invariant probability measure, and write

$$\begin{aligned} \frac{d}{dt}\mu S(t)\{\eta(x) = 0 \;\forall\; 1 \leq x \leq n\}\bigg|_{t=0} &= -\lambda\mu\{\eta(0) = 1, \eta(x) = 0 \;\forall\; 1 \leq x \leq n\} \\ &\quad - \lambda\mu\{\eta(n+1) = 1, \eta(x) = 0 \;\forall\; 1 \leq x \leq n\} \\ &\quad + \sum_{k=1}^{n} \mu\{\eta(k) = 1, \eta(x) = 0 \;\forall \text{ other } 1 \leq x \leq n\}. \end{aligned} \tag{1.1}$$

Let ν be the nontrivial invariant measure, and let

$$F(n) = \frac{\nu\{\eta(0) = 1, \eta(x) = 0 \;\forall\; 1 \leq x \leq n-1\}}{\nu\{\eta(0) = 1\}}, \quad n \geq 1,$$

be the tail probabilities of the conditional spacing distribution. If ν satisfied the strong positive correlations property, it would follow that

$$\nu\{\eta(k) = 1, \eta(x) = 0 \;\forall \text{ other } 1 \leq x \leq n\} \geq F(k)F(n-k+1)\nu\{\eta(0) = 1\} \tag{1.2}$$

for all $1 \leq k \leq n$. Using this in (1.1), we obtain (since ν is symmetric with respect to reflection in $\mathbb{Z}$, translation invariant and invariant)

$$\sum_{k=1}^{n} F(k)F(n-k+1) \leq 2\lambda F(n+1) \tag{1.3}$$

for all $n \geq 1$. The translation invariance of ν implies that

$$M = \sum_{n=1}^{\infty} F(n) < \infty.$$

Summing (1.3) for $n \geq 1$, and using $F(1) = 1$, we obtain

$$M^2 \leq 2\lambda(M-1).$$

Therefore, the discriminant of the corresponding quadratic is ≥ 0, so that $\lambda \geq 2$. We conclude that the strong positive correlations property fails for $\lambda < 2$. It probably fails for all larger λ as well. In fact, one can enlarge the class of λ's for which this conclusion holds by using a few other expressions of the type (1.1), but for sets of sites which are not intervals. However, since this is a negative result, there is not much point in pursuing this generalization.

Given what we have done so far, the Holley–Liggett proof of survival of the basic one dimensional contact process for $\lambda \geq 2$ can be summarized in the following way:

STEP 1. Let μ be a stationary renewal measure (so that (1.2) holds with equality), chosen so that (1.3) holds with equality. It is easy to solve these equations explicitly for $\lambda \geq 2$:

$$F(n+1) = \binom{2n}{n} \frac{1}{(n+1)(2\lambda)^n}, \quad n \geq 0.$$

Then the right side of (1.1) is zero, so that

$$\frac{d}{dt}\mu S(t)\{\eta(x) = 0 \ \forall \ x \in A\} \leq 0 \tag{1.4}$$

(in fact, $= 0$) for $t = 0$, $A = \{1, \ldots, n\}$ and all $n \geq 1$.

STEP 2. Show that (1.4) holds at $t = 0$ for all finite sets A.

STEP 3. Use the duality relation

$$P^\eta\{\eta_t = 0 \text{ on } A\} = P^A\{\eta = 0 \text{ on } A_t\},$$

where A_t is the finite contact process, to show that (1.4) for $t = 0$ and all A implies (1.4) for all $t \geq 0$ and all A.

STEP 4. Conclude that $\mu S(t)\{\eta(x) = 0\} \downarrow$ in t, and hence does not converge to one.

The hard part of the argument is step 2. In that part, one proves and uses the fact that the renewal sequence corresponding to the density $f(n) = F(n) - F(n+1)$ is decreasing in n, and this in turn follows from the logarithmic convexity of f. The details can be found in Section 1 of Chapter VI of Liggett (1985).

This argument is quite old, but little was done to see if it could be used more generally until the last few years. The recent applications of this technique can be found in the papers in the bibliography by Katori and Konno, and by Liggett. One type of extension, which we will not describe here, involves proofs of survival for contact processes which are not spatially homogeneous. (See my papers in the Harris and Spitzer volumes and in the 1992 Annals of Probability.) We will describe two other types of extension.

First, there is the possibility of obtaining better upper bounds for λ_c for the basic process. To get a better upper bound, one needs to find something more general than a renewal measure to use as the initial distribution in step 1 above. Various possibilities suggest themselves, but the following observation makes one particularly natural: Use a modification of the Gibbs formalism to write a probability measure μ as

$$\mu(\eta) = K \exp\left(\sum_{\eta=0 \text{ on } A} J_A \right) \tag{1.5}$$

for some potential J_A. It turns out that μ is a renewal measure iff $J_A = 0$ for all A's other than intervals. So, to obtain an upper bound λ_n for λ_c, one can consider measures given formally by (1.5), where $J_A = 0$ for all A's other than intervals or sets of diameter $\leq n$. The nonzero J_A's can be specified by requiring that (1.4) hold with equality at $t = 0$ for all A's which are intervals or sets of diameter $\leq n$. One finds that $\lambda_1 = 2$ (this is the Holley–Liggett bound), and $\lambda_2 = 1.941227....$ A computation suggests that $\lambda_3 = 1.89349....$ The full details of the proof are worked out for $n = 2$ in a forthcoming paper.

The second extension we will describe involves proving survival for modifications of the contact process — in this case, for one with a non nearest neighbor interaction. This extension will be important in the next section. The process is the same as the basic one dimensional contact process, except that the infection rate at $x \in Z$ is given by λ if at least one of $\eta(x-2)$, $\eta(x-1)$, $\eta(x+1)$, $\eta(x+2)$ takes the value 1, and the rate is 0 otherwise. The survival of this process for $\lambda = 1$ is proved in a paper to appear by again using a renewal measure as initial distribution. The analogue of (1.3) with equality which must be solved in step 1 is now

$$\begin{gathered} F(2) = \frac{1}{\lambda+1}, \ F(3) = \frac{1}{(\lambda+1)^2}, \ F(4) + F(5) = \frac{1}{\lambda(\lambda+1)^2}, \text{ and} \\ \sum_{k=1}^{n} F(k)F(n-k+1) = 4\lambda F(n+1) + 2\lambda F(n+2) \text{ for } n \geq 4. \end{gathered} \tag{1.6}$$

This does not seem too different from (1.3) (with equality), but now it cannot be solved explicitly, and this leads to significant difficulties. In fact, the proof that there is a solution of (1.6) (for $\lambda = 1$) which is decreasing and for which the corresponding renewal sequence has the required monotonicity and convexity properties is computer assisted. We proved analytically that there is a solution which has the required properties for $n \geq 1000$, and then computed the first 1000 values of F and the renewal sequence accurately enough to check the required properties for those n.

As will be seen in the next section, it is essential for our application of this result that we know survival for $\lambda = 1$; $\lambda = 1.01$ would not do. The technique (using an initial renewal measure) appears to work for $\lambda > .985$, and we were simply lucky that $.985 < 1$. This is one motivation for obtaining better upper bounds — next time we might not be so lucky.

2. Coexistence in Threshold Voter Models

Recently, Cox and Durrett (1991) introduced a new class of particle systems called threshold voter models. Their behavior turns out to be quite different from those of the (linear) voter models treated in Chapter V of my book, and several papers have been written about them by subsets of Andjel, Cox, Durrett, Mountford, Liggett and Steif.

The d-dimensional threshold voter model with parameter N is the spin system η_t on $\{0,1\}^{\mathbb{Z}^d}$ in which a flip at $x \in \mathbb{Z}^d$ occurs at rate 1 if $\eta(y) \neq \eta(x)$ for some y with $\|y - x\| \leq N$, and at rate 0 otherwise ($\|\cdot\|$ can be any reasonable norm, such as the l_p norm). We will say that the process coexists if it has a nontrivial invariant measure (i.e., one which puts no mass on the $\equiv 0$ or $\equiv 1$ configurations). Otherwise, we will say that the process clusters. Our objective is to determine for each (N, d) whether the process coexists or clusters. The well known answer to this problem for the linear voter model is that clustering occurs for all N if $d = 1, 2$ and coexistence occurs for all N if $d \geq 3$.

Cox and Durrett (1991) proved clustering for $N = d = 1$. It is particularly easy to see in this case that there is no nontrivial invariant measure which is translation invariant. The argument is based on the following computation, which is valid for any translation invariant μ:

$$\frac{d}{dt}\mu S(t)\bigg|_{t=0} = -\mu(101) - \mu(010) \leq 0.$$

Cox and Durrett also proved that coexistence occurs for each d if N is sufficiently large, and conjectured that coexistence occurs in all cases except $N = d = 1$. This conjecture was recently proved by Liggett.

The argument is based on a comparison with the threshold contact process, in which $1 \to 0$ at rate one and $0 \to 1$ at rate λ if $\eta(y) \neq \eta(x)$ for some y with $\|y - x\| \leq N$, and at rate 0 otherwise. Here is an outline:

Step 1. For every (N, d), if the threshold contact process survives for $\lambda = 1$, then the threshold voter model coexists.

Step 2. For any λ, if the threshold contact process survives for (N, d), then it survives for (N', d') with $N' \geq N$ and $d' \geq d$.

Step 3. For any λ, if the threshold contact process survives for $(N, d) = (2, 1)$, then it survives for $(N, d) = (1, 2)$.

Step 4. The threshold contact process with $\lambda = 1$, $N = 2$, $d = 1$ survives.

The only difficult step is the last one, but that is the one discussed in the previous section.

Consider now a more general class of threshold voter models: A flip occurs at x at rate 1 if $\eta(y) \neq \eta(x)$ for at least T y's with $\|y - x\| \leq N$. The previously discussed model is the case $T = 1$. Many open problems remain if $T > 1$. Here are some results which have been proved: (n denotes the cardinality of the neighborhood $\{x : \|x\| \leq N\}$.)

1. If $d = 1$ and $T = N$ $(= \frac{1}{2}(n-1))$, then the process clusters. Furthermore, if the initial distribution is translation invariant, then the limiting distribution as $t \to \infty$ exists (and is a mixture of the pointmasses on 0 and 1). (Andjel, Liggett and Mountford (1992))
2. If $T = \theta n$ with $\theta < \frac{1}{4}$ and N is sufficiently large, then there is coexistence. (Durrett (1992))
3. If $T > \frac{1}{2}(n-1)$, then the process fixates, in the sense that each site flips only finitely often. (Durrett and Steif (1993)).

In case $T = \theta n$ with $\frac{1}{4} < \theta < \frac{1}{2}$, Durrett and Steif conjecture that clustering occurs if N is sufficiently large. The behavior of the system when N is small is open if $T \leq \frac{1}{2}(n-1)$ ($<$ if $d = 1$).

Bibliography

When I wrote my 1985 book, I tried to include in the list of references essentially all of the papers on interacting particle systems which had been written up to that time (which covered about 15 years). There were approximately 350 of them. Since then, I have maintained a list of papers and books on this subject, and I am taking this opportunity to share this list with the world at large. There are over 300 entries, representing the accomplishments in this field over the past eight years.

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