Competing Brownian Particles

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We have $N$ Brownian particles on the real line:

$$X_1(t), \ldots, X_N(t).$$

Rank them from bottom to top:

$$X_{(1)}(t) \leq X_{(2)}(t) \leq \ldots \leq X_{(N)}(t).$$

The particle which is currently the $k$th lowest has rank $k$.

**Main Rule:** the particle which currently has rank $k$ moves as a Brownian motion with drift $g_k$ and diffusion $\sigma_k^2$.

When particles exchange ranks, they also exchange drift and diffusion coefficients.
When two or more particles are tied, how to assign ranks?

We resolve ties in favor of the lexicographic order: assign lower ranks to particles $X_i$ with smaller indices $i$.

So the SDE governing dynamics of the particles is

$$dX_i(t) = \sum_{k=1}^{N} 1(X_i \text{ has rank } k \text{ at time } t) \left( g_k dt + \sigma_k dW_i(t) \right).$$

This system was introduced in (Banner, Fernholz, Karatzas, 2005)
It has a weak solution, unique in law (Bass, Pardoux, 1987)
**Motivation**

- **Stochastic Portfolio Theory**
  Banner, Fernholz, Karatzas, 2005
  Pal, Chatterjee, 2010
  Jourdain, Reygner, 2013

- **Similar systems with totally asymmetric collisions**
  Ferrari, Spohn, Weiss, 2015

- **Scaling limits of asymmetrically colliding random walks**
  Karatzas, Pal, Shkolnikov, 2016

- **Discretized version of McKean-Vlasov nonlinear diffusion**
  Shkolnikov, 2012
  Jourdain, Reygner, 2013
  Dembo, Shkolnikov, Varadhan, Zeitouni, 2015
  Kolli, Shkolnikov, 2016
This is the process taking values in the orthant $\mathbb{R}_+^{N-1}$:

$$Z(t) = (Z_1(t), \ldots, Z_{N-1}(t))',$$

defined as follows: for $k = 1, \ldots, N - 1$, $t \geq 0$,

$$Z_k(t) = X_{(k+1)}(t) - X_{(k)}(t).$$
This is a **semimartingale reflected Brownian motion (SRBM)** in the orthant.

- In the interior of the orthant, it behaves as an \((N-1)\)-dimensional Brownian motion with certain drift vector and covariance matrix.

- At each **face** \(\{z_k = 0\}\) of the boundary, it is reflected back in the orthant, not normally, but obliquely.

Allows connections with SRBM theory (Harrison, Williams, others)
Define \( \bar{g}_k := \frac{1}{k} (g_1 + \ldots + g_k) \), \( k = 1, \ldots, N \).

There exists a stationary gap distribution \( \pi \) if and only if

\[
\bar{g}_k > \bar{g}_N, \quad k = 1, \ldots, N - 1
\]

that is, if the average drift for a few bottom particles is greater than the average drift for all particles.

If this stationary distribution exists, then it is unique. Regardless of the initial condition, \( Z(t) \Rightarrow \pi \) as \( t \to \infty \). Convergence in total variation, exponentially fast.

Pal, Pitman, 2008
Banner, Fernholz, Ichiba, Karatzas, Papathanakos, 2011
In case of the skew-symmetry condition

$$\sigma_k^2 - \sigma_{k-1}^2 = \sigma_{k+1}^2 - \sigma_k^2, \quad k = 2, \ldots, N - 1,$$

the stationary distribution $\pi$ is the product of exponentials:

$$\pi = \prod_{k=1}^{N-1} \text{Exp} \left( \frac{4k(\bar{g}_k - \bar{g}_N)}{\sigma_k^2 + \sigma_{k+1}^2} \right).$$

$\text{Exp}(\alpha)$ is the exponential distribution with rate $\alpha$ and mean $\alpha^{-1}$.

Pal, Pitman, 2008
Banner, Fernholz, Ichiba, Karatzas, Papathanakos, 2011
$$g_1 = 1, \quad g_2 = \ldots = g_N = 0,$$

$$\sigma_1 = \sigma_2 = \ldots = \sigma_N = 1.$$

It is called so because the bottom-ranked particle supports all other particles on its shoulders, like the ancient Atlas hero.

It has the following stationary gap distribution:

$$\pi = \prod_{k=1}^{N-1} \text{Exp} \left( 2 \frac{N - k}{N} \right).$$
Infinite Systems of Competing Brownian Particles

Infinitely many Brownian particles on the real line: $X_1(t), X_2(t), \ldots$. Rank them from the bottom upward:

$$X_{(1)}(t) \leq X_{(2)}(t) \leq X_{(3)}(t) \leq \ldots$$

Main Rule: the particle which currently has rank $k$ moves as a Brownian motion with drift $g_k$ and diffusion $\sigma_k^2$. When particles exchange ranks, they also exchange drift and diffusion coefficients.

$$dX_i(t) = \sum_{k=1}^{\infty} 1 (X_i \text{ has rank } k \text{ at time } t) (g_k dt + \sigma_k dW_i(t)).$$

Introduced in (Shkolnikov, 2011) and studied further in (Ichiba, Karatzas, Shkolnikov, 2013; S, 2015; Dembo, Tsai, 2015; S, Tsai, 2016).
Unlike the finite system, the infinite system might not always exist, even in the weak sense.

**Why?** Because it might not be possible to rank these particles.

Assume for simplicity that \( g_1 = g_2 = \ldots = 0 \) and \( \sigma_1 = \sigma_2 = \ldots = 1 \). Start infinitely many i.i.d. Brownian motions from the same initial point. Then it is impossible to rank them from bottom to top.

This shows that we need to have some condition on initial values \( x_n = X_n(0), \ n = 1, 2, \ldots \) They should be far enough apart, or, alternatively, tend to infinity \( x_n \to \infty \) fast enough.
An assumption on initial conditions $x_n = X_n(0)$, $n = 1, 2, \ldots$

Tending to infinity fast enough?

$$\sum_{n=1}^{\infty} \exp(-\alpha x_n^2) < \infty \quad \text{for all} \quad \alpha > 0.$$ 

E.g. $x_n = cn$, $x_n = c \log n$ work, but $x_n = c(\log n)^{1/2}$ does not.
Weak Existence and Uniqueness

Theorem (Ichiba, Karatzas, Shkolnikov, 2013; S, 2015)

Suppose $X_n(0) = x_n \rightarrow \infty$ fast enough.

In addition, at least one of two conditions holds:

(a) for some $n_0$, $g_{n_0} = g_{n_0+1} = \ldots$ and $\sigma_{n_0} = \sigma_{n_0+1} = \ldots$

(b) $\sigma_n = 1$ for all $n$, and $\sum_{n=1}^{\infty} g_n^2 < \infty$.

Then the system exists in the weak sense and is unique in law.
The gap process for infinite systems $X_1(t), X_2(t), \ldots$ is defined similarly to the finite case: it is an $\mathbb{R}^\infty_+$-valued process

$$Z(t) = (Z_1(t), Z_2(t), Z_3(t), \ldots), \quad t \geq 0,$$

$$Z_k(t) = X_{(k+1)}(t) - X_{(k)}(t),$$

where $X_{(k)}$ is the $k$th ranked particle.

We are interested in stationary gap distributions $\pi$ and convergence $Z(t) \Rightarrow \pi$ as $t \to \infty$. 
From now on, consider the case

\[ g_1 = \ldots = g_M = 1, \quad g_{M+1} = g_{M+2} = \ldots = 0, \]

\[ \sigma_1 = \sigma_2 = \ldots = 1. \]

The results are available in a more general setting, but here they are simple. A particular case is the infinite Atlas model, \( M = 1 \):

\[ g_1 = 1, \quad g_2 = g_3 = \ldots = 0; \quad \sigma_1 = \sigma_2 = \ldots = 1. \]
Find stationary gap distribution $\pi$ for the infinite Atlas model. Stationary gap distribution for Atlas model with $N$ particles is

$$\pi_N = \bigotimes_{k=1}^{N-1} \text{Exp} \left( 2 \frac{N-k}{N} \right).$$

For each $k$, letting $N \to \infty$, we get:

$$2 \frac{N-k}{N} \to 2.$$ 

It is reasonable to conjecture that $\pi = \bigotimes_{k=1}^{\infty} \text{Exp}(2)$. This was formally proved in Pal, Pitman, 2008.
Theorem (S, Tsai, 2016)

There are infinitely many stationary gap distributions:

\[ \pi_a = \bigotimes_{k=1}^{\infty} \text{Exp}(2(k \wedge M) + ak), \ a \geq 0. \]

In particular, for the infinite Atlas model we have:

\[ \pi_a = \bigotimes_{k=1}^{\infty} \text{Exp}(2 + ka), \ a \geq 0. \]

This includes the result from Pal, Pitman, 2008:

\[ \pi_0 = \bigotimes_{k=1}^{\infty} \text{Exp}(2). \]
Consider again the stationary gap distribution:

\[ \pi_a = \bigotimes_{k=1}^{\infty} \text{Exp}(2(k \wedge M) + ak), \; a \geq 0. \]

For \( a > 0 \), there are \( O(\exp(aL)) \) particles on \([0, L]\), as \( L \to \infty \).

The quantity of particles is growing exponentially fast when you go to infinity. This creates a negative drift:

\[ \mathbb{E} \left[ X_{(k)}(t) - X_{(k)}(0) \right] = -\frac{a}{2} t. \]

The sheer density of particles at the top pushes the bottom particles down with (on average) linear speed.
Two probability measures $P$ and $Q$ on $\mathbb{R}_+^\infty$. We say:

\[ P \preceq Q : \quad Q \text{ stochastically dominates } P, \]

if for all $x_1, x_2, \ldots \geq 0$,

\[ P\left( [x_1, \infty) \times [x_2, \infty) \times \ldots \right) \leq Q\left( [x_1, \infty) \times [x_2, \infty) \times \ldots \right). \]
Recall: for finite systems, the gap process always converges to its stationary distribution. as \( t \to \infty \).

For infinite systems, this is no longer true, because there are multiple stationary gap distributions and therefore multiple domains of convergence.

Among stationary gap distributions, this one plays a special role:

\[
\pi_0 = \bigotimes_{k=1}^{\infty} \text{Exp}(2(k \wedge M)).
\]
Theorem (S, 2015)

(a) The family \((Z(t), t \geq 0)\) of random variables is tight in \(\mathbb{R}^\infty\).

(b) Every weak limit point of \(Z(t)\) as \(t \to \infty\) is stochastically smaller than the stationary distribution \(\pi_0\).

(c) If \(Z(0)\) is stochastically larger than \(\pi_0\), then \(Z(t) \Rightarrow \pi_0\) as \(t \to \infty\).

Part (c) describes domain of convergence for the distribution \(\pi_0\).
Infinite system of competing Brownian particles with

\[ \sigma_1 = \sigma_2 = \ldots = 1 \quad \text{and} \]

\[ \lim_{n \to \infty} g_n = 0, \quad \sum_{n=1}^{\infty} g_n^2 < \infty. \]

Define the average of \( n \) bottom drifts:

\[ \bar{g}_n := \frac{1}{n} (g_1 + \ldots + g_n), \quad n = 1, 2, \ldots \]
Theorem (S-Tsai, 2016)

For \( a > -2 \inf_{n \geq 1} \bar{g}_n \), the following is a stationary gap distribution:

\[
\pi_a = \bigotimes_{n=1}^{\infty} \exp \left( 2(g_1 + \ldots + g_n) + na \right).
\]

In this distribution, for every ranked particle \( X_{(k)} \),

\[
\mathbb{E} \left( X_{(k)}(t) - X_{(0)}(t) \right) = -\frac{a}{2} t.
\]

Next, we apply this result for two special cases.
Infinitely many driftless Brownian particles $X_1(t), X_2(t), \ldots$

$$g_1 = g_2 = \ldots = 0, \quad \sigma_1 = \sigma_2 = \ldots = 1.$$  

(S-Tsai, 2016) A family of stationary gap distributions:

$$\pi_a = \bigotimes_{k=1}^{\infty} \text{Exp}(ka), \quad a > 0.$$  

As in the previous case, there is an implied drift:

$$\mathbb{E} \left[ X_{(k)}(t) - X_{(k)}(0) \right] = -\frac{a}{2} t.$$  

Even without any original drifts, the sheer density of particles is enough to create new drift and a stationary gap distribution.

This is a continuous analogue of (Aizenman, Ruzmaikina, 2005)
Infinite system of competing Brownian particles with negative drift at the bottom:

\[ g_1 = -1, \ g_2 = g_3 = \ldots = 0, \ \sigma_1 = \sigma_2 = \ldots = 1. \]

(S-Tsai, 2016) A family of stationary gap distributions:

\[ \pi_a = \bigotimes_{k=1}^{\infty} \text{Exp}(-2 + ka), \ a > 2. \]

Even with negative bottom drift, if the exponential density of particles above is large enough, it can outweigh this drift.

The particles above chase the bottom particle fast enough.
Indexed by all integers: $X_i(t), \ i \in \mathbb{Z}$.

Similar weak existence and uniqueness in law results.

Gap process: $Z(t) = (Z_n(t))_{n \in \mathbb{Z}}$, takes values in $\mathbb{R}^\mathbb{Z}_+$. 

**Theorem (S, 2016)**

Assume $\sigma_n = 1$ for all $n$. Every sequence $(\lambda_n)_{n \in \mathbb{Z}}$ of positive numbers which satisfies

$$\frac{1}{2} \lambda_{n-1} - \lambda_n + \frac{1}{2} \lambda_{n+1} = g_{n+1} - g_n, \quad n \in \mathbb{Z},$$

corresponds to stationary gap distribution: $\pi = \otimes_{n \in \mathbb{Z}} \text{Exp}(\lambda_n)$. 

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Two-Sided Infinite Systems: Examples

\[ g_n = 0 \text{ for all } n: \pi_a = \otimes \text{Exp}(a), \ a > 0. \] Poisson point process with constant intensity is preserved by Brownian dynamics.

\[ g_n = 1(n > 0): \pi_{a,b} = \otimes \text{Exp}(a + bn + n_+), \ a > 0, \ b \in [-1, 0]. \] Two-parameter family of stationary gap distributions.

\[ g_n = 1(n \leq 0): \text{no stationary gap distributions} \]

\[ Z(t) \Rightarrow 0 \text{ as } t \to \infty. \]
Competing Lévy Particles
Rank-based systems driven by Levy processes rather than Brownian motions. (Shkolnikov, 2011; S, 2016)

Hybrid Models
Drift and diffusion coefficients depending on ranks and names of particles. (Banner, Fernholz, Ichiba, Karatzas, Papathanakos, 2011; Fernholz, Ichiba, Karatzas, 2013)

Asymmetric Collisions
Particles having different mass and moving away with different speed when colliding. (Karatzas, Pal, Shkolnikov, 2016)
Prove weak existence and uniqueness for the infinite system under weaker conditions on drift and diffusion coefficients:

\[
\sup_{n \geq 1} |g_n| < \infty, \quad \sup_{n \geq 1} \sigma_n^2 < \infty.
\]

Are there other stationary gap distributions except \( \pi_a, a \geq 0, \) and their mixtures?

Find domains of convergence for every stationary distribution.
Thanks!