

TRIPLE AND SIMULTANEOUS COLLISIONS OF COMPETING BROWNIAN PARTICLES

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ABSTRACT. Consider a finite system of competing Brownian particles on the real line. Each particle moves as a Brownian motion, with drift and diffusion coefficients depending only on its current rank relative to the other particles. A triple collision occurs if three particles are at the same position at the same moment. A simultaneous collision occurs if at a certain moment, there are two distinct pairs of particles such that in each pair, both particles occupy the same position. These two pairs of particles can overlap, so a triple collision is a particular case of a simultaneous collision. We find a necessary and sufficient condition for a.s. absence of triple and simultaneous collisions, continuing the work of Ichiba, Karatzas, Shkolnikov (2013). Our results are also valid for the case of asymmetric collisions, when the local time of collision between the particles is split unevenly between them; these systems were introduced in Karatzas, Pal, Shkolnikov (2012).

1. INTRODUCTION

This paper is devoted to finite systems of competing Brownian particles. First, let us informally describe these systems. Fix $N \geq 2$, the quantity of particles. Take real-valued parameters g_1, \dots, g_N and positive real-valued parameters $\sigma_1, \dots, \sigma_N$. Consider N particles, moving on the real line. At each time, rank them from the left to the right: the particle which is currently the leftmost one has rank 1, the second leftmost particle has rank 2, etc., up to the rightmost particle, which has rank N . As particles move, they can exchange ranks. We shall explain below how to resolve ties between particles. The particles move according to the following law: for each $k = 1, \dots, N$, the particle with (current) rank k moves as a Brownian motion with drift coefficient g_k and diffusion coefficient σ_k^2 , for each $k = 1, \dots, N$. Thus, the dynamics of each particle depends on its current rank among other particles.

Let us now formally define these systems. Consider the standard setting: a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbf{P})$ with the filtration satisfying the usual conditions.

Any one-dimensional Brownian motion with zero drift and unit diffusion coefficients starting from the origin is called a *standard Brownian motion*. The symbol a' denotes the transpose of (a vector or a matrix) a . We write $1(C)$ for the indicator of the event C .

For every vector $x = (x_1, \dots, x_N)' \in \mathbb{R}^N$, let \mathbf{p} be the permutation on $\{1, \dots, N\}$ with the following properties:

- (i) it orders the components of x : $x_{\mathbf{p}(i)} \leq x_{\mathbf{p}(j)}$ for $1 \leq i \leq j \leq N$;
- (ii) ties are resolved in the lexicographic order: if $1 \leq i < j \leq N$ and $x_{\mathbf{p}(i)} = x_{\mathbf{p}(j)}$, then $\mathbf{p}(i) < \mathbf{p}(j)$.

There exists a unique permutation $\mathbf{p} = \mathbf{p}_x$ which satisfies these two properties. We shall call it *the ranking permutation* for the vector x . For example, if $x = (1, -1, 0, 0)'$, then $\mathbf{p}_x(1) = 2$, $\mathbf{p}_x(2) = 3$, $\mathbf{p}_x(3) = 4$, $\mathbf{p}_x(4) = 1$. We write $x_{(i)} = x_{\mathbf{p}_x(i)}$ for $i = 1, \dots, N$, so that $x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(N)}$ are the ranked components of the vector x .

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Definition 1.1. Take i.i.d. standard $(\mathcal{F}_t)_{t \geq 0}$ -Brownian motions W_1, \dots, W_N . For a continuous \mathbb{R}^N -valued process

$$X = (X(t), t \geq 0), \quad X(t) = (X_1(t), \dots, X_N(t))',$$

denote by $\mathbf{p}_t \equiv \mathbf{p}_{X(t)}$ the ranking permutation for the vector $X(t)$ for every $t \geq 0$. Suppose this process satisfies the following SDE:

$$(1) \quad dX_i(t) = \sum_{k=1}^N \mathbf{1}(\mathbf{p}_t(k) = i) [g_k dt + \sigma_k dW_i(t)], \quad i = 1, \dots, N.$$

Then this process X is called a *classical system of N competing Brownian particles* with *drift coefficients* g_1, \dots, g_N and *diffusion coefficients* $\sigma_1^2, \dots, \sigma_N^2$. For $k = 1, \dots, N$, the process

$$Y_k = (Y_k(t), t \geq 0), \quad Y_k(t) := X_{\mathbf{p}_t(k)}(t) \equiv X_{(k)}(t),$$

is called the *k th ranked particle*. If $\mathbf{p}_t(k) = i$, then we say that the particle $X_i(t) = Y_k(t)$ at time t has *name i* and *rank k* .

These systems were introduced in the paper [2] for financial modeling; on this topic, see subsection 1.5. The coefficients of the SDE (1) are piecewise constant functions of $X_1(t), \dots, X_N(t)$, so weak existence and uniqueness in law for such systems follow from [4]. By definition, the ranked particles satisfy

$$Y_1(t) \leq Y_2(t) \leq \dots \leq Y_N(t).$$

Definition 1.2. A *triple collision at time t* occurs if there exists a rank $k = 2, \dots, N - 1$ such that $Y_{k-1}(t) = Y_k(t) = Y_{k+1}(t)$.

A triple collision is sometimes an undesirable phenomenon. For example, existence and uniqueness of a strong solutions of the SDE (1) has been proved only up to the first moment of a triple collision, see [33, Theorem 2]. In this paper, we give a necessary and sufficient condition for absence of triple collisions with probability one. First, let us define some related concepts.

Definition 1.3. A *simultaneous collision at time t* occurs if there are ranks $k \neq l$ such that such that $Y_k(t) = Y_{k+1}(t)$, $Y_l(t) = Y_{l+1}(t)$.

A triple collision is a particular case of a simultaneous collision.

The main result of this article is as follows.

Theorem 1.4. *Consider a system from Definition 1.1.*

(i) *Suppose the sequence $(\sigma_n^2)_{1 \leq n \leq N}$ is concave, that is,*

$$(2) \quad \sigma_{k+1}^2 - \sigma_k^2 \leq \sigma_k^2 - \sigma_{k-1}^2, \quad k = 2, \dots, N - 1.$$

Then, with probability one, there are no triple and no simultaneous collisions at any time $t > 0$.

(ii) *If the condition (2) fails for a certain $k = 2, \dots, N - 1$, then with positive probability there exists a moment $t > 0$ such that there is a triple collision between particles with ranks $k - 1$, k , and $k + 1$ at time t .*

The proof of this result is given in Section 4. We can state a remarkable corollary of this theorem.

Corollary 1.5. *Take a system from Definition 1.1. Suppose a.s. there are no triple collisions at any moment $t > 0$. Then a.s. there are no simultaneous collisions at any moment $t > 0$.*

It is interesting that a system of $N = 4$ particles can have a.s. no simultaneous collisions of the form

$$(3) \quad Y_1(t) = Y_2(t), \quad Y_3(t) = Y_4(t),$$

and at the same time triple collisions with positive probability. For example, if you take

$$\sigma_1 = \sigma_4 = 1, \quad \text{and} \quad \sigma_2 = \sigma_3 = 1 - \varepsilon \quad \text{for sufficiently small } \varepsilon > 0,$$

then there are a.s. no simultaneous collisions of the form (3), but with positive probability there is a triple collision of ranked particles Y_1 , Y_2 , and Y_3 , and with positive probability there is a triple collision of ranked particles Y_2 , Y_3 , and Y_4 . If

$$\sigma_1 = \sigma_3 = 1, \quad \text{and} \quad \sigma_2 = \sigma_4 = 1 + \varepsilon \quad \text{for sufficiently small } \varepsilon > 0,$$

then there are a.s. no simultaneous collisions of the form (3), and a.s. no triple collisions of ranked particles Y_1 , Y_2 , and Y_3 , but with positive probability there is a triple collision of ranked particles Y_2 , Y_3 , and Y_4 . This is shown in the companion paper [54, Subsection 1.2].

1.1. Collision local times. Consider a system of competing Brownian particles from Definition 1.1. Define the processes $B_1 = (B_1(t), t \geq 0), \dots, B_N = (B_N(t), t \geq 0)$ as follows:

$$B_k(t) = \sum_{i=1}^N \int_0^t 1(\mathbf{p}_s(k) = i) dW_i(s).$$

One can calculate that $\langle B_i, B_j \rangle_t = \delta_{ij}t$; therefore, these are i.i.d. standard Brownian motions. For $k = 2, \dots, N$, let the process $L_{(k-1,k)} = (L_{(k-1,k)}(t), t \geq 0)$ be the semimartingale local time at zero of the nonnegative semimartingale $Y_k - Y_{k-1}$. For notational convenience, we let $L_{(0,1)}(t) \equiv 0$ and $L_{(N,N+1)}(t) \equiv 0$. Then the ranked particles Y_1, \dots, Y_N satisfy the following dynamics:

$$(4) \quad Y_k(t) = Y_k(0) + g_k t + \sigma_k B_k(t) + \frac{1}{2} L_{(k-1,k)}(t) - \frac{1}{2} L_{(k,k+1)}(t), \quad k = 1, \dots, N.$$

The equation (4) was deduced in [1, Lemma 1] and [3, Theorem 2.5]; see also [2, Section 3] and [31, Chapter 3].

The process $L_{(k-1,k)}$ is called the *local time of collision between the particles Y_{k-1} and Y_k* . One can regard the local time $L_{(k-1,k)}(t)$ to be the total amount of push between the $(k-1)$ st and the k th ranked particles Y_{k-1} and Y_k accumulated by time t . This amount of push is necessary and sufficient to keep the particle Y_k to the right of the particle Y_{k-1} , so that $Y_{k-1}(t) \leq Y_k(t)$.

When these two particles collide, the amount of push is split evenly between them: the amount $(1/2)L_{(k-1,k)}(t)$ goes to the right-sided particle Y_k and pushes it to the right; the equal amount $(1/2)L_{(k-1,k)}(t)$ (with the minus sign) goes to the left-sided particle Y_{k-1} and pushes it to the left. One possible physical interpretation of this phenomenon: the ranked particles have the same mass; so, when they collide, they get the same amount of push.

The local time process $L_{(k-1,k)}$ has the following properties: $L_{(k-1,k)}(0) = 0$, $L_{(k-1,k)}$ is nondecreasing, and it can increase only when $Y_{k-1}(t) = Y_k(t)$, that is, when particles with ranks $k-1$ and k collide. We can formally write the last property as

$$(5) \quad \int_0^\infty 1(Y_k(t) \neq Y_{k-1}(t)) dL_{(k-1,k)}(t) = 0.$$

1.2. Systems with asymmetric collisions. If we change coefficients $1/2$ in (4) to some other values, we get the model from the paper [37]. The local times in this new model are split unevenly between the two colliding particles, as if they had different mass. Let us now formally define this model. First, let us describe its parameters. Let $N \geq 2$ be the quantity of particles. Fix real numbers g_1, \dots, g_N and positive real numbers $\sigma_1, \dots, \sigma_N$, as before. In addition, fix real numbers $q_1^+, q_1^-, \dots, q_N^+, q_N^-$, satisfying the following conditions:

$$q_{k+1}^+ + q_k^- = 1, \quad k = 1, \dots, N-1; \quad 0 < q_k^\pm < 1, \quad k = 1, \dots, N.$$

Definition 1.6. Take i.i.d. standard $(\mathcal{F}_t)_{t \geq 0}$ -Brownian motions B_1, \dots, B_N . Consider a continuous adapted \mathbb{R}^N -valued process

$$Y = (Y(t), t \geq 0), \quad Y(t) = (Y_1(t), \dots, Y_N(t))',$$

and $N - 1$ continuous adapted real-valued processes

$$L_{(k-1,k)} = (L_{(k-1,k)}(t), t \geq 0), \quad k = 2, \dots, N,$$

with the following properties:

- (i) $Y_1(t) \leq \dots \leq Y_N(t)$, $t \geq 0$,
- (ii) the process Y satisfies the following system of equations:

$$(6) \quad Y_k(t) = Y_k(0) + g_k t + \sigma_k B_k(t) + q_k^+ L_{(k-1,k)}(t) - q_k^- L_{(k,k+1)}(t), \quad k = 1, \dots, N.$$

We let $L_{(0,1)}(t) \equiv 0$ and $L_{(N,N+1)}(t) \equiv 0$ for notational convenience.

(iii) for each $k = 2, \dots, N$, the process $L_{(k-1,k)} = (L_{(k-1,k)}(t), t \geq 0)$ has the properties mentioned above: $L_{(k-1,k)}(0) = 0$, $L_{(k-1,k)}$ is nondecreasing and satisfies (5).

Then the process Y is called a *system of N competing Brownian particles with asymmetric collisions*, with drift coefficients g_1, \dots, g_N , diffusion coefficients $\sigma_1^2, \dots, \sigma_N^2$, and parameters of collision q_1^\pm, \dots, q_N^\pm . For each $k = 1, \dots, N$, the process $Y_k = (Y_k(t), t \geq 0)$ is called the *k th ranked particle*. For $k = 2, \dots, N$, the process $L_{(k-1,k)}$ is called the *local time of collision between the particles Y_{k-1} and Y_k* .

The state space of the process Y is $\mathcal{W}^N := \{y = (y_1, \dots, y_N)' \in \mathbb{R}^N \mid y_1 \leq y_2 \leq \dots \leq y_N\}$. Strong existence and pathwise uniqueness for Y and L are proved in [37, Section 2.1].

Remark 1.7. Triple and simultaneous collisions for these systems are defined similarly to Definitions 1.2 and 1.3.

In the case of asymmetric collisions, we can also define a corresponding named system of competing Brownian particles.

Definition 1.8. Consider a continuous adapted process

$$X = (X(t), t \geq 0), \quad X(t) = (X_1(t), \dots, X_N(t))'.$$

Suppose \mathbf{p}_t is the ranking permutation of $X(t)$ for $t \geq 0$, as before, and

$$Y_k(t) \equiv X_{\mathbf{p}_t(k)}(t), \quad k = 1, \dots, N, \quad t \geq 0,$$

Let $L_{(k-1,k)} = (L_{(k-1,k)}(t), t \geq 0)$ be the semimartingale local time at zero of $Y_k - Y_{k-1}$, for $k = 2, \dots, N$; and $L_{(0,1)}(t) \equiv L_{(N,N+1)}(t) \equiv 0$ for notational convenience, as before.

Then this system $X = (X_1, \dots, X_N)'$ is governed by the following SDE: for $i = 1, \dots, N$ and $t \geq 0$,

$$\begin{aligned} dX_i(t) &= \sum_{k=1}^N \mathbf{1}(\mathbf{p}_t(k) = i) (g_k dt + \sigma_k dW_i(t)) \\ &\quad + \sum_{k=1}^N \mathbf{1}(\mathbf{p}_t(k) = i) (q_k^- - (1/2)) dL_{(k,k+1)}(t) \\ &\quad + \sum_{k=1}^N \mathbf{1}(\mathbf{p}_t(k) = i) (q_k^+ - (1/2)) dL_{(k-1,k)}(t). \end{aligned}$$

It is called a *system of named competing Brownian particles with drift coefficients $(g_n)_{1 \leq n \leq N}$, diffusion coefficients $(\sigma_n^2)_{1 \leq n \leq N}$, and parameters of collision $(q_n^\pm)_{1 \leq n \leq N}$* .

The ranked particles (Y_1, \dots, Y_N) from Definition 1.8 form a system of ranked competing Brownian particles in the sense of Definition 1.6. However, unlike the system Y from Definition 1.6, which exists and is unique in a strong sense up to the infinite time horizon, the system X from Definition 1.8 is known to have strong solutions only up to the first moment of a triple collision, see [37]. This provides a motivation to find a condition which guarantees absence of triple collisions. Here, we prove a necessary and sufficient condition for a.s. lack of triple collisions.

Theorem 1.9. *Consider a system of competing Brownian particles with asymmetric collisions from Definition 1.6.*

(i) *Suppose the following condition is true:*

$$(7) \quad (q_{k-1}^- + q_{k+1}^+) \sigma_k^2 \geq q_k^- \sigma_{k+1}^2 + q_k^+ \sigma_{k-1}^2, \quad k = 2, \dots, N-1.$$

Then, with probability one, there are no triple and no simultaneous collisions at any time $t > 0$.

(ii) *If the condition (7) is violated for some $k = 2, \dots, N-1$, then with positive probability there exists a moment $t > 0$ such that there is a triple collision between particles with ranks $k-1$, k , and $k+1$ at time t .*

Note that Theorem 1.4 is a particular case of this theorem for $q_k^\pm = 1/2$, $k = 1, \dots, N$. Corollary 1.5 is also true for systems with asymmetric collisions.

1.3. Method of proof: reduction to an SRBM in the orthant. Let us informally describe a stochastic process called a *semimartingale reflected Brownian motion (SRBM) in the positive multidimensional orthant* $S := \mathbb{R}_+^d$, where $\mathbb{R}_+ := [0, \infty)$ and $d \geq 1$ is the dimension. We formally define an SRBM in subsection 2.1.

Fix the parameters of an SRBM: a *drift vector* $\mu \in \mathbb{R}^d$, a *covariance matrix*: a $d \times d$ -positive definite symmetric matrix $A = (a_{ij})_{1 \leq i, j \leq d}$, and a *reflection matrix*: a $d \times d$ -matrix $R = (r_{ij})_{1 \leq i, j \leq d}$ with $r_{ii} = 1$, $i = 1, \dots, d$. Then an SRBM in the orthant S with parameters R, μ, A , denoted by $\text{SRBM}^d(R, \mu, A)$, is a Markov process with state space S which:

(i) behaves as a d -dimensional Brownian motion with drift vector μ and covariance matrix A in the interior of the orthant S ;

(ii) on each face $S_i = \{x \in S \mid x_i = 0\}$ of the boundary ∂S , the process is reflected in the direction of r_i , the i th column of R .

If $r_i = e_i$, where e_i is the i th standard basis vector in \mathbb{R}^d , then the reflection is called *normal*. Otherwise, it is called *oblique*.

For a system of N competing Brownian particles (the classical system or the one with asymmetric collisions), the gaps $Z_k(t) = Y_{k+1}(t) - Y_k(t)$, $k = 1, \dots, N-1$, between adjacent ranked particles form an SRBM in the orthant \mathbb{R}_+^{N-1} : see subsection 2.2. If there is a simultaneous collision $Y_k(t) = Y_{k+1}(t)$ and $Y_l(t) = Y_{l+1}(t)$, then $Z_k(t) = Z_l(t) = 0$. In other words, a simultaneous collision is equivalent to the gap process hitting non-smooth parts of the boundary of the orthant \mathbb{R}_+^{N-1} . In Theorem 2.12, subsection 2.3, we state a necessary and sufficient condition for an SRBM to a.s. avoid non-smooth parts of the boundary. This theorem is proved in Section 3. In Section 4, we translate these results into the language of competing Brownian particles, and prove Theorem 1.4 and Theorem 1.9.

We find whether this SRBM hits *non-smooth parts* $S_i \cap S_j$, $i \neq j$ of the boundary ∂S . This corresponds to triple or simultaneous collisions of competing Brownian particles. This connection is established in subsection 2.2.

1.4. Relation to previous results. For classical systems of competing Brownian particles from Definition 1.1, some significant partial results on the triple collision problem were known before. In particular, a necessary and sufficient condition for absence of triple collisions for systems with only three particles is obtained in [32]. In the article [33], it is proved that the condition (2)

from Theorem 1.4 is necessary. For systems with asymmetric collisions from [37], some sufficient conditions for absence of triple collisions were found, but these are not necessary conditions.

In the companion paper [54], we find a sufficient condition for avoiding collisions of four or more particles (*multiple collisions*), as well as *multicollisions*: when a few particles collide and at the same time other few particles collide. An example of a multicollision is $Y_1(t) = Y_2(t) = Y_3(t)$, $Y_5(t) = Y_6(t)$ and $Y_7(t) = Y_8(t)$. A simultaneous collision (for example, $Y_1(t) = Y_2(t)$ and $Y_3(t) = Y_4(t)$) is a particular case of a multicollision. In particular, as mentioned above, we can find examples of a system of four particles avoiding simultaneous collisions of the type (3) but having triple collisions with positive probability.

We can also define a reflected Brownian motion in domains which are more general than the orthant. In particular, a *two-dimensional wedge* is a subset of \mathbb{R}^2 of the form

$$\{(r \cos \theta, r \sin \theta) \mid 0 \leq r < \infty, \quad 0 \leq \theta \leq \xi\}$$

(where $\xi \in (0, \pi)$ is the angle of this wedge). A reflected Brownian motion with unit drift vector and identity covariance matrix was studied in [57]. The latter paper provides a necessary and sufficient condition for this process to a.s. avoid hitting the origin (the corner of the wedge). In [60], the Hausdorff dimension of the set of times when this process hits the corner was found. More generally, we can define a reflected Brownian motion in a convex polyhedron in \mathbb{R}^d : see [13] and [14]. In [61], a reflected Brownian motion in a polyhedral domain was constructed under the so-called *skew-symmetry condition*, see (13) and (24). It was shown that under this condition, it does not hit non-smooth parts of the boundary. These results are important and are applied in this article.

Let us also mention some related sources on nonattainability of lower-dimensional manifolds by a diffusion process: the papers [21], [47], [48], [8], and the book [22].

1.5. Motivation and historical review. The original motivation to study classical systems of competing Brownian particles came from Stochastic Finance. An observed phenomenon of real-world stock markets is that stocks with smaller capitalizations have larger growth rates and larger volatilities. This can be captured by the classical model of competing Brownian particles: just let $g_1 > \dots > g_N$ and $\sigma_1 > \dots > \sigma_N$, and suppose that for $i = 1, \dots, N$, the quantity $e^{X_i(t)}$ is the capitalization of the i th stock at time t . For financial applications and market models similar to this rank-based model, see the articles [1], [17], [38], the book [16, Chapter 5] and a somewhat more recent survey [19, Chapter 3].

Classical systems from Definition 1.1 were studied in [31], [1], [45], [9], [46], [34], [19]. There are several generalizations of these systems: [55] (systems of competing Levy particles), [45], [33] (infinite systems of competing Brownian particles); [18], [17], [1] (*second-order stock market models*, when drift and diffusion coefficients depend on both ranks and names).

Systems of competing Brownian particles with asymmetric collisions are related to the theory of exclusion processes: it was proved in [37, Section 3] that these systems are scaling limits of asymmetrically colliding random walks, which constitute a certain type of exclusion processes. In addition, these systems are also related to random matrices and random surfaces evolving according to the KPZ equation, see [20].

Studying an SRBM in the orthant is motivated by queueing theory. An SRBM in the orthant is the *heavy traffic limit* for series of queues, when the traffic intensity at each queue tends to one, see [50], [51], [24]. We can also define an SRBM in general convex polyhedral domains in \mathbb{R}^d , see [14]. An SRBM in the orthant and in convex polyhedra has been extensively studied, see the survey [62], and articles [27], [26], [29], [28], [61], [52], [56], [15], [13], [10], [24], [6], [7], [14], [12], [11], [25], [58], [59], [63], [39], [40], [43], [49], [36], [41], [42], [57], [60].

1.6. Notation. We denote by I_k the $k \times k$ -identity matrix. For a vector $x = (x_1, \dots, x_d)' \in \mathbb{R}^d$, let $\|x\| := (x_1^2 + \dots + x_d^2)^{1/2}$ be its Euclidean norm. For any two vectors $x, y \in \mathbb{R}^d$, their dot product

is denoted by $x \cdot y = x_1y_1 + \dots + x_dy_d$. We compare vectors x and y componentwise: $x \leq y$ if $x_i \leq y_i$ for all $i = 1, \dots, d$; $x < y$ if $x_i < y_i$ for all $i = 1, \dots, d$; similarly for $x \geq y$ and $x > y$. We compare matrices of the same size componentwise, too. For example, we write $x \geq 0$ for $x \in \mathbb{R}^d$ if $x_i \geq 0$ for $i = 1, \dots, d$; $C = (c_{ij})_{1 \leq i, j \leq d} \geq 0$ if $c_{ij} \geq 0$ for all i, j .

Fix $d \geq 1$, and let $I \subseteq \{1, \dots, d\}$ be a nonempty subset. Write its elements in the order of increase: $I = \{i_1, \dots, i_m\}$, $1 \leq i_1 < i_2 < \dots < i_m \leq d$. For any $x \in \mathbb{R}^d$, let $[x]_I := (x_{i_1}, \dots, x_{i_m})'$. For any $d \times d$ -matrix $C = (c_{ij})_{1 \leq i, j \leq d}$, let $[C]_I := (c_{i_k i_l})_{1 \leq k, l \leq m}$.

2. SEMIMARTINGALE REFLECTED BROWNIAN MOTION (SRBM) IN THE ORTHANT

2.1. Definition of an SRBM. Fix $d \geq 1$, the dimension. Recall that $\mathbb{R}_+ := [0, \infty)$, and let $S := \mathbb{R}_+^d$ be the d -dimensional positive orthant. Its boundary consists of d faces $S_i = \{x \in S \mid x_i = 0\}$, $i = 1, \dots, d$. Take the parameters R, μ, A described in Subsection 1.2: a $d \times d$ -matrix R with diagonal elements equal to one, a $d \times d$ positive definite symmetric matrix A , and a vector $\mu \in \mathbb{R}^d$. Assume the usual setting: a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbf{P})$ with the filtration satisfying the usual conditions.

Definition 2.1. Take a continuous function $\mathcal{X} : \mathbb{R}_+ \rightarrow \mathbb{R}^d$ with $\mathcal{X}(0) \in S$. A *solution to the Skorohod problem in the positive orthant S with reflection matrix R and driving function \mathcal{X}* is a continuous function $\mathcal{Z} : \mathbb{R}_+ \rightarrow S$ such that there exists another continuous function $\mathcal{Y} : \mathbb{R}_+ \rightarrow \mathbb{R}^d$ with the following properties:

- (i) for every $t \geq 0$, we have: $\mathcal{Z}(t) = \mathcal{X}(t) + R\mathcal{Y}(t)$;
- (ii) for every $i = 1, \dots, d$, the function \mathcal{Y}_i is nondecreasing, satisfies $\mathcal{Y}_i(0) = 0$ and can increase only when $\mathcal{Z}_i(t) = 0$, that is, when $\mathcal{Z}(t) \in S_i$. We can write the last property formally as

$$\int_0^\infty \mathcal{Z}_i(t) d\mathcal{Y}_i(t) = 0.$$

Remark 2.2. This definition can also be stated for a finite time horizon, that is, for functions $\mathcal{X}, \mathcal{Y}, \mathcal{Z}$ defined on $[0, T]$ instead of \mathbb{R}_+ .

Definition 2.3. Suppose $B = (B(t), t \geq 0)$ is an $((\mathcal{F}_t)_{t \geq 0}, \mathbf{P})$ -Brownian motion in \mathbb{R}^d with drift vector μ and covariance matrix A . A solution $Z = (Z(t), t \geq 0)$ to the Skorohod problem in S with reflection matrix R and driving function B is called a *semimartingale reflected Brownian motion*, or SRBM, *in the positive orthant S with reflection matrix R , drift vector μ and covariance matrix A* . It is denoted by $\text{SRBM}^d(R, \mu, A)$. The function \mathcal{Y} is called the *vector of regulating processes*, and its i th component \mathcal{Y}_i is called the *regulating process corresponding to the face S_i* . The process B is called the *driving Brownian motion*. We say that Z starts from $x \in S$ if $Z(0) = x$ a.s.

Definition 2.4. Take a $d \times d$ -matrix $R = (r_{ij})_{1 \leq i, j \leq d}$. It is called a *reflection matrix* if $r_{ii} = 1$ for $i = 1, \dots, d$. It is called *nonnegative* if all its elements are nonnegative, that is, if $R \geq 0$; it is called *strictly nonnegative* if it is nonnegative and $r_{ii} > 0$ for $i = 1, \dots, d$. It is called an *\mathcal{S} -matrix* if there exists a vector $u \in \mathbb{R}^d$, $u > 0$ such that $Ru > 0$. Any submatrix of R of the form $[R]_I$, where $I \subseteq \{1, \dots, d\}$ is a nonempty subset, is called a *principal submatrix* (this includes the matrix R itself). The matrix R is called *completely- \mathcal{S}* if each of its principal submatrices is an \mathcal{S} -matrix. It is called a *\mathcal{Z} -matrix* if $r_{ij} \leq 0$ for $i \neq j$. It is called *strictly inverse-nonnegative* if it is invertible and its inverse R^{-1} is a strictly nonnegative matrix. It is called a *nonsingular \mathcal{M} -matrix* if it is both completely- \mathcal{S} and a \mathcal{Z} -matrix.

The following lemma is a useful characterization of reflection nonsingular \mathcal{M} -matrices; its proof is given in the Appendix.

Lemma 2.5. *Suppose R is a $d \times d$ reflection matrix. Then the following statements are equivalent:*

- (i) R is a nonsingular \mathcal{M} -matrix;

- (ii) R is a strictly inverse-nonnegative \mathcal{Z} -matrix;
- (iii) $R = I_d - Q$, where Q is a nonnegative matrix with spectral radius less than 1.

We are ready to state an existence and uniqueness result, proved in [27, Theorem 1], see also [62, Theorem 2.1]. This is not the most general result (for which the reader might want to see [52], [56] and [62, Theorem 2.3]), but it is sufficient for our purposes.

Proposition 2.6. *Suppose R is a $d \times d$ reflection nonsingular \mathcal{M} -matrix.*

(i) *For every continuous driving function $\mathcal{X} : \mathbb{R}_+ \rightarrow \mathbb{R}^d$ with $\mathcal{X}(0) \in S$, the Skorohod problem in the orthant S with reflection matrix R has a unique solution.*

(ii) *Take a vector $\mu \in \mathbb{R}^d$ and a $d \times d$ positive definite symmetric matrix A . For every $x \in S$, there exists in the strong sense an SRBM $^d(R, \mu, A)$ starting from x , and it is pathwise unique. These processes, starting from different $x \in S$, form a Feller continuous strong Markov family.*

Now we define a key concept: hitting non-smooth parts of the boundary ∂S of the orthant S . (We already mentioned this in the Introduction.) This concept is a counterpart of triple and simultaneous collisions for systems of competing Brownian particles.

Definition 2.7. The set

$$S^0 := \cup_{1 \leq i < j \leq d} (S_i \cap S_j) \subseteq \partial S$$

is called *non-smooth parts of the boundary ∂S* . An S -valued process $Z = (Z(t), t \geq 0)$ *hits non-smooth parts of the boundary at time t* if there exist $i, j = 1, \dots, d, i \neq j$ such that $Z_i(t) = Z_j(t) = 0$. We say that the process Z *hits non-smooth parts of the boundary* if there exists $t > 0$ such that it hits non-smooth parts of the boundary at time t . If such $t > 0$ does not exist, then we say that Z *avoids non-smooth parts of the boundary*.

2.2. Connection between an SRBM in the orthant and systems of competing Brownian particles. In this subsection, we show that the gaps between adjacent particles in a system of competing Brownian particles form an SRBM in the orthant.

Definition 2.8. Consider a system of N competing Brownian particles (a classical system from Definition 1.1 or a system with asymmetric collisions from Definition 1.6). Let Y_1, \dots, Y_N be the ranked particles. Then the \mathbb{R}_+^{N-1} -valued process

$$Z = (Z(t), t \geq 0), \quad Z(t) = (Z_1(t), \dots, Z_{N-1}(t))',$$

defined by

$$Z_k(t) = Y_{k+1}(t) - Y_k(t), \quad t \geq 0, \quad k = 1, \dots, N-1,$$

is called the *gap process* for this system of competing Brownian particles.

Lemma 2.9. *For a system of competing Brownian particles from Definition 1.6, the gap process is an SRBM $^{N-1}(R, \mu, A)$, where*

$$(8) \quad R = \begin{bmatrix} 1 & -q_2^- & 0 & 0 & \dots & 0 & 0 \\ -q_2^+ & 1 & -q_3^- & 0 & \dots & 0 & 0 \\ 0 & -q_3^+ & 1 & -q_4^- & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 & -q_{N-1}^- \\ 0 & 0 & 0 & 0 & \dots & -q_{N-1}^+ & 1 \end{bmatrix},$$

$$(9) \quad A = \begin{bmatrix} \sigma_1^2 + \sigma_2^2 & -\sigma_2^2 & 0 & 0 & \dots & 0 & 0 \\ -\sigma_2^2 & \sigma_2^2 + \sigma_3^2 & -\sigma_3^2 & 0 & \dots & 0 & 0 \\ 0 & -\sigma_3^2 & \sigma_3^2 + \sigma_4^2 & -\sigma_4^2 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & \sigma_{N-2}^2 + \sigma_{N-1}^2 & -\sigma_{N-1}^2 \\ 0 & 0 & 0 & 0 & \dots & -\sigma_{N-1}^2 & \sigma_{N-1}^2 + \sigma_N^2 \end{bmatrix},$$

$$(10) \quad \mu = (g_2 - g_1, g_3 - g_2, \dots, g_N - g_{N-1})'.$$

The matrix R in (8) is a nonsingular \mathcal{M} -matrix.

Corollary 2.10. For a classical system of competing Brownian particles from Definition 1.1, the gap process is an SRBM $^{N-1}(R, \mu, A)$, where

$$(11) \quad R = \begin{bmatrix} 1 & -1/2 & 0 & 0 & \dots \\ -1/2 & 1 & -1/2 & 0 & \dots \\ 0 & -1/2 & 1 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix},$$

while A and μ are given by (9) and (10), respectively.

The proof can be found in [2] for classical systems or in [37] for systems with asymmetric collisions. However, for the sake of completeness we give the full proof here.

Proof. Using the equation (6), we get the following equation for $Z_k = Y_{k+1} - Y_k$:

$$\begin{aligned} Z_k(t) = & Z_k(0) + (g_{k+1} - g_k)t + \sigma_{k+1}B_{k+1}(t) - \sigma_k B_k(t) \\ & + (q_{k+1}^+ + q_k^-)L_{(k,k+1)}(t) - q_k^+L_{(k-1,k)}(t) - q_{k+1}^-L_{(k+1,k+2)}(t). \end{aligned}$$

Let

$$\overline{W}_k(t) = Z_k(0) + (g_{k+1} - g_k)t + \sigma_{k+1}B_{k+1}(t) - \sigma_k B_k(t), \quad k = 1, \dots, N-1, \quad t \geq 0.$$

Recall that $q_{k+1}^+ + q_k^- = 1$ for $k = 1, \dots, N-1$. Therefore,

$$Z_k(t) = \overline{W}_k(t) + L_{(k,k+1)}(t) - q_k^+L_{(k-1,k)}(t) - q_{k+1}^-L_{(k+1,k+2)}(t).$$

The \mathbb{R}^{N-1} -valued process $\overline{W} = (\overline{W}_1, \dots, \overline{W}_{N-1})'$ is an $(\mathcal{F}_t)_{t \geq 0}$ -Brownian motion in $N-1$ dimensions, with drift vector $\mu = (g_2 - g_1, \dots, g_N - g_{N-1})'$ and covariance matrix A given by (9). Indeed, B_1, \dots, B_N are i.i.d. standard Brownian motions. Therefore,

$$\langle \overline{W}_k \rangle_t = \langle \sigma_{k+1}B_{k+1}(t) - \sigma_k B_k(t) \rangle_t = (\sigma_k^2 + \sigma_{k+1}^2)t,$$

$$\langle \overline{W}_k, \overline{W}_{k+1} \rangle_t = \langle \sigma_{k+1}B_{k+1}(t) - \sigma_k B_k(t), \sigma_{k+2}B_{k+2}(t) - \sigma_{k+1}B_{k+1}(t) \rangle_t = -\sigma_{k+1}^2 t,$$

and $\langle \overline{W}_k, \overline{W}_l \rangle_t = 0$ for $|k - l| \geq 2$. The process $L_{(k,k+1)}$ for each $k = 1, \dots, N-1$ satisfies the following conditions: it starts from zero, that is, $L_{(k,k+1)}(0) = 0$; it is nondecreasing, and can increase only when $Y_k = Y_{k+1}$, or, equivalently, when $Z_k = 0$. The rest is trivial. \square

Remark 2.11. A system of competing Brownian particles has a simultaneous collision at time t if and only if the gap process hits non-smooth parts S^0 of the boundary ∂S at time t . This is our method of proof: we state and prove results for an SRBM, and then we translate them into the language of systems of competing Brownian particles.

2.3. Main Results for an SRBM. In this subsection, we state a necessary and sufficient condition for an SRBM a.s. to avoid non-smooth parts of the boundary. For the rest of this subsection, fix $d \geq 2$. Suppose R is a $d \times d$ reflection nonsingular \mathcal{M} -matrix. Fix a vector $\mu \in \mathbb{R}^d$ and a $d \times d$ positive definite symmetric matrix A . Recall the notation $S = \mathbb{R}_+^d$ and consider the process $Z = (Z(t), t \geq 0) = \text{SRBM}^d(R, \mu, A)$, starting from some point $x \in S$.

Let us give a necessary and sufficient condition for an SRBM a.s. not hitting non-smooth parts of the boundary ∂S of the orthant S .

Theorem 2.12. (i) *Suppose the following condition holds:*

$$(12) \quad r_{ij}a_{jj} + r_{ji}a_{ii} \geq 2a_{ij}, \quad 1 \leq i, j \leq d.$$

Then with probability one, there does not exist $t > 0$ such that Z hits non-smooth parts of the boundary at time t .

(ii) *If the condition (12) is violated for some $1 \leq i < j \leq d$, then with positive probability there exists $t > 0$ such that $Z_i(t) = Z_j(t) = 0$.*

Remark 2.13. The condition (12) can be written in the matrix form as $RD + DR^T \geq 2A$, where $D = \text{diag}(A) = \text{diag}(a_{11}, \dots, a_{dd})$ is the diagonal $d \times d$ -matrix with the same diagonal entries as A . The case when we have equality in (12) instead of inequality, is very important: the condition

$$(13) \quad RD + DR^T = 2A \quad \Leftrightarrow \quad r_{ij}a_{jj} + r_{ji}a_{ii} = 2a_{ij}, \quad 1 \leq i, j \leq d,$$

is called the *skew-symmetry condition*. This is a very important and well-studied case: see [29], [28], [61], [62, Theorem 3.5]. For example, under this condition, the SRBM has the product-of-exponentials stationary distribution.

Remark 2.14. Whether an $\text{SRBM}^d(R, \mu, A)$ a.s. avoids non-smooth parts of the boundary depends only on the matrices R and A , not on the initial condition $Z(0)$ or the drift vector μ . Some general results of this type are shown in subsection 3.2, Lemma 3.3. But the actual probability of hitting non-smooth parts of the boundary, if it is positive, does depend on μ and the initial condition, see Remark 3.4.

3. PROOF OF THEOREM 2.12

3.1. Outline of the proof. We can define a reflected Brownian motion not only in the orthant, but in more general domains: namely, in convex polyhedra, see [14]. Similarly to an SRBM in the orthant, this is a process which behaves as a Brownian motion in the interior of the domain and is reflected according to a certain vector at each face of the boundary. We can reduce an SRBM in the orthant with an arbitrary covariance matrix to a reflected Brownian motion in a convex polyhedron with identity covariance matrix. This construction is carried out in detail in subsection 3.5, Lemma 3.18.

Let us give a brief preview here. Consider an SRBM $Z = (Z(t), t \geq 0)$ in the orthant \mathbb{R}_+^d with covariance matrix A . Consider the process

$$(14) \quad \bar{Z} = (\bar{Z}(t), t \geq 0), \quad \bar{Z}(t) = A^{-1/2}Z(t),$$

which is a reflected Brownian motion in the domain $A^{-1/2}\mathbb{R}_+^d := \{A^{-1/2}z \mid z \in \mathbb{R}_+^d\}$ with identity covariance matrix.

For a reflected Brownian motion in a polyhedral domain with identity covariance matrix, a sufficient condition (the *skew-symmetry condition*) for a.s. not hitting non-smooth parts of the boundary is known, see [61, Theorem 1.1]. Note that there are two forms of the skew-symmetry condition. One is for an SRBM in the orthant with arbitrary covariance matrix, which is (13). The other is for a reflected Brownian motion in a convex polyhedron with identity covariance matrix, which was introduced in [61]; in our paper, it is going to be given in (24). In Lemma 3.21 we prove

that under this linear transformation (14), these two conditions match. This justifies why they bear the same name. This allows us (in Lemma 3.24) to prove part (i) of Theorem 2.12 under the skew-symmetry condition (13).

Now, we need to show this for a more general condition (12). We reduce this general case to the case of the skew-symmetry condition (13) by stochastic comparison (Lemma 3.9). We introduce an SRBM with new reflection matrix \tilde{R} which satisfies the skew-symmetry condition and such that $\tilde{R} \geq R$.

To prove part (ii), we first consider the case $d = 2$. The domain $A^{-1/2}\mathbb{R}_+^2$ is in this case a *two-dimensional wedge*, which can be written in polar coordinates

$$x_1 = r \cos \theta, \quad x_2 = r \sin \theta,$$

as

$$0 \leq r < \infty, \quad \xi_2 \leq \theta \leq \xi_1,$$

where ξ_1, ξ_2 are angles such that $\xi_2 \leq \xi_1 \leq \xi_2 + \pi$. We mentioned that a reflected Brownian motion in this domain with zero drift vector and identity covariance matrix was studied in [57], [58], [59], [60]. For this process, hitting non-smooth parts of the boundary means hitting the corner of the wedge (the origin). The result [57, Theorem 2.2] gives a necessary and sufficient condition for a.s. avoiding the corner. Using the linear transformation (14), we can then translate these results for an SRBM in the positive quadrant with general covariance matrix. This proves (ii) for $d = 2$.

To prove Theorem 2.12 for the general d , we again use comparison techniques. We consider any two components Z_i, Z_j of the process $Z = (Z(t), t \geq 0) = \text{SRBM}^d(R, \mu, A)$, and compare them with a two-dimensional SRBM using Corollary 3.10.

Some parts of the calculations in this proof below have been done in certain previous articles. For example, the linear transformation $z \mapsto A^{-1/2}z$ and the way it transforms an SRBM in the orthant have been studied in the following articles: [28, Section 9, Theorem 23] (general dimension, under the skew-symmetry condition); [37, Proposition 2] (dimension $d = 2$). However, to make the exposition as lucid and self-contained as possible, we decided to do all calculations from scratch.

Remark 3.1. In this article, we define a reflected Brownian motion in Definition 2.3 as a semimartingale. Similarly, in the article [14] a reflected Brownian motion in a convex polyhedron is defined in a semimartingale form; we present this in Definition 3.11. However, in the papers [57] and [61], a reflected Brownian motion is not given in a semimartingale form. Instead, it is defined as a solution to a certain submartingale problem: see Definition 3.16. We use the semimartingale definition, and in Lemma 3.17 we prove that the semimartingale form of a reflected Brownian motion also satisfies the submartingale definition. This shows that we can indeed use the results from [57] and [61].

3.2. Girsanov removal of drift and independence of the initial conditions. In this subsection, fix $d \geq 1$. Let R be a $d \times d$ reflection nonsingular \mathcal{M} -matrix. Let A be a $d \times d$ symmetric positive definite matrix, and let $\mu \in \mathbb{R}^d$. For every $x \in S$, denote by \mathbf{P}_x the probability measure corresponding to the $\text{SRBM}^d(R, \mu, A)$ starting from x .

Definition 3.2. For a nonempty subset $I \subseteq \{1, \dots, d\}$, let $S_I = \{x \in S \mid x_i = 0, i \in I\}$. This is called an *edge* of the orthant S .

For example, $S_{\{i,j\}} = S_i \cap S_j$ for $i \neq j$ is a piece of the non-smooth parts of the boundary ∂S . In this article, we are interested in an $\text{SRBM}^d(R, \mu, A)$ hitting or avoiding these edges. But for this subsection, we shall work with a general edge S_I of S .

The main result of this subsection is that the property of an SRBM to a.s. avoid S_I is independent of the starting point $x \in S$ and of the drift vector μ . The proof is postponed until the end of this subsection.

Proposition 3.3. *Let $Z = (Z(t) \geq 0)$ be an SRBM $^d(R, \mu, A)$. Let*

$$p(x, R, \mu, A) = \mathbf{P}_x(\exists t > 0 : Z(t) \in S_I).$$

Fix a $d \times d$ reflection nonsingular \mathcal{M} -matrix R and a positive definite symmetric $d \times d$ matrix A . Then one of these two statements is true:

- *For all $\mu \in \mathbb{R}^d$ and $x \in S$, we have: $p(x, R, \mu, A) = 0$: (the edge S_I is avoided).*
- *For all $\mu \in \mathbb{R}^d$ and $x \in S$, we have: $p(x, R, \mu, A) > 0$: (the edge S_I is hit).*

Remark 3.4. We can reformulate Lemma 3.3 as follows: whether an SRBM $^d(R, \mu, A)$ hits the edge S_I does not depend on the initial conditions and the drift vector μ ; it depends only on the reflection matrix R and the covariance matrix A .

However, suppose SRBM $^d(R, \mu, A)$ hits the edge S_I , so the probability $p(x, R, \mu, A)$ is positive. What is its exact value? This probability *does* depend on the drift vector μ and the initial condition $x \in S$. Let us give a one-dimensional example: a reflected Brownian motion on the positive half-line \mathbb{R}_+ with no drift. With probability one, it hits the origin (which is the same as hitting the edge $S_{\{1\}}$). But a reflected Brownian motion on \mathbb{R}_+ with positive drift b , starting from $x > 0$, hits the origin with probability e^{-2bx} , see [5, Part 2, Section 2, formula 2.0.2]. This does depend on the drift b and the initial condition x .

Definition 3.5. We say that an SRBM $^d(R, \mu, A)$ *avoids non-smooth parts of the boundary* ∂S of the orthant S if it avoids every edge S_I with $|I| = 2$. Otherwise, we say that an SRBM $^d(R, \mu, A)$ *hits non-smooth parts of the boundary* ∂S .

From the discussion just above, we see: the property of hitting non-smooth parts of the boundary is independent of the initial condition x and of the drift vector μ . It depends only on R and A . We can also see it from Theorem 2.12: the condition (12) involves only elements of R and A .

3.3. Proof of Proposition 3.3. We split the proof of Lemma 3.3 in two steps. First, we show independence of a starting point $x \in S$ in Lemma 3.6, then of a drift vector $\mu \in \mathbb{R}^d$ in Lemma 3.7, using the Girsanov transformation.

Lemma 3.6. *For fixed parameters R, μ, A of an SRBM, we have: either $p(x, R, \mu, A) = 0$ for all $x \in S$, or $p(x, R, \mu, A) > 0$ for all $x \in S$. In other words, either an SRBM $^d(R, \mu, A)$ hits the edge S_I , or it avoids the edge S_I .*

Proof. Since the family of the processes $Z = (Z(t), t \geq 0) = \text{SRBM}^d(R, \mu, A)$, starting from different points $x \in S$, is Feller continuous, the function

$$f(z) := \mathbf{P}_z(\exists t > 0 : Z(t) \in S_I)$$

is continuous on S . Let $P^t(x, C) = \mathbf{P}_x(Z(t) \in C)$ be the transition function for the SRBM $^d(R, \mu, A)$. By the Markov property,

$$(15) \quad \mathbf{P}_z(\exists t > 1 : Z(t) \in S_I) = \int_S P^1(z, dy) f(y).$$

But

$$(16) \quad \mathbf{P}_z(\exists t > 1 : Z(t) \in S_I) \leq \mathbf{P}_z(\exists t > 0 : Z(t) \in S_I) = f(z).$$

Combining (15) and (16), we have:

$$\int_S f(y) P^1(z, dy) \leq f(z).$$

Suppose for some $z_0 \in S$ we have: $f(z_0) > 0$. Since f is continuous, there exists an open neighborhood U of z_0 in S such that $f(z) \geq f(z_0)/2 > 0$ for $z \in U$. But U has positive Lebesgue measure, and so $P^1(z, U) > 0$ for $z \in S$. Therefore, $f(z) \geq P^1(z, U) f(z_0)/2 > 0$ for all $z \in S$.

We have proved that if $f(z_0) > 0$ for at least one $z_0 \in S$, then $f(z) > 0$ for all $z \in S$. This completes the proof of the lemma. \square

Lemma 3.7. *Fix a nonempty subset $I \subseteq \{1, \dots, d\}$. Then an $\text{SRBM}^d(R, \mu, A)$ avoids S_I if and only if an $\text{SRBM}^d(R, 0, A)$ avoids S_I .*

Proof. Using Lemma 3.6, without loss of generality, fix a starting point $z \in S$, the same for both processes. Let $Z = \text{SRBM}^d(R, \mu, A)$, starting from z , and let $\bar{Z} = \text{SRBM}^d(R, 0, A)$, starting from z . Let P, \bar{P} be the distributions of the processes Z, \bar{Z} on the space $C(\mathbb{R}_+, \mathbb{R}^d)$ of continuous functions $\mathbb{R}_+ \rightarrow \mathbb{R}^d$. For every $T > 0$, let \mathcal{G}_T be the σ -subalgebra of the Borel σ -algebra of $C(\mathbb{R}_+, \mathbb{R}^d)$, generated by the values of $x(s)$, $0 \leq s \leq T$ for all functions $x \in C(\mathbb{R}_+, \mathbb{R}^d)$. By the Girsanov theorem, for every $T > 0$, the restrictions $P|_{\mathcal{G}_T}$ and $\bar{P}|_{\mathcal{G}_T}$ are mutually absolutely continuous: they have common events of probability one. Therefore, the following statements are equivalent:

- With probability 1, there is no $t \in (0, T]$ such that $Z(t) \in S_I$;
- With probability 1, there is no $t \in (0, T]$ such that $\bar{Z}(t) \in S_I$.

Suppose that with probability 1, there is no $t > 0$ such that $Z_i(t) = 0$ for each $i \in I$; then for every $T > 0$, with probability 1, there is no $t \in (0, T]$ such that $\bar{Z}_i(t) = 0$. Since $T > 0$ is arbitrary, we have: with probability 1, there is no $t > 0$ such that $\bar{Z}_i(t) = 0$ for each $i \in I$. The converse statement is proved similarly. \square

3.4. Stochastic comparison for an SRBM. Let us introduce the concept of *stochastic domination*, or *domination in law*.

Definition 3.8. Fix $d \geq 1$ and take two \mathbb{R}^d -valued processes $Z = (Z(t), t \geq 0)$, $\bar{Z} = (\bar{Z}(t), t \geq 0)$. We say that Z is *stochastically dominated by \bar{Z}* if for every $t \geq 0$ and $y \in \mathbb{R}^d$ we have:

$$\mathbf{P}(Z(t) \geq y) \leq \mathbf{P}(\bar{Z}(t) \geq y).$$

We say that Z is *pathwise dominated by \bar{Z}* if a.s. for all $t \geq 0$ we have: $Z(t) \leq \bar{Z}(t)$.

If the processes Z and \bar{Z} are Markov, then by changing the probability space we can move from stochastic domination to pathwise domination, see [35, Theorem 5]. There is a well-developed theory of stochastic domination and pathwise domination for processes with oblique reflection in the orthant. The most general result in this area is [49, Theorem 4.1], see also [41, Theorem 1.1(i)], [23, Theorem 3.1], [43, Theorem 6(i)]. The following proposition is an immediate corollaries of [49, Theorem 4.1].

Proposition 3.9. *Take two $d \times d$ reflection nonsingular \mathcal{M} -matrices R, \bar{R} such that $\bar{R} \leq R$. Fix a vector $\mu \in \mathbb{R}^d$ and a positive definite symmetric $d \times d$ -matrix A . Let*

$$Z = \text{SRBM}^d(R, \mu, A), \quad \bar{Z} = \text{SRBM}^d(\bar{R}, \mu, A), \quad \text{such that } Z(0) \preceq \bar{Z}(0).$$

Then $Z \preceq \bar{Z}$.

Here is another useful statement, proved in [53, Corollary 3.6], which is applied later in this article.

Corollary 3.10. *Let $d \geq 1$ and take a $d \times d$ reflection nonsingular \mathcal{M} -matrix. Take a vector $\mu \in \mathbb{R}^d$ and a positive definite symmetric $d \times d$ -matrix A . Fix a nonempty subset $I \subseteq \{1, \dots, d\}$ with $|I| = p$, $1 \leq p < d$. Let*

$$Z = \text{SRBM}^d(R, \mu, A), \quad \bar{Z} = \text{SRBM}^p([R]_I, [\mu]_I, [A]_I)$$

such that $[Z(0)]_I = \bar{Z}(0)$ in law. Then $[Z]_I \preceq \bar{Z}$.

3.5. An SRBM in a convex polyhedron. Let us give a definition of an SRBM in convex polyhedra from [14]. Fix the dimension $d \geq 1$. First, let us define the state space, a polyhedral domain $\mathcal{P} \subseteq \mathbb{R}^d$. Fix $m \geq 1$, the number of edges. Let $n_1, \dots, n_m \in \mathbb{R}^d$ be unit vectors, and let $b_1, \dots, b_m \in \mathbb{R}$. The domain \mathcal{P} is defined by

$$(17) \quad \mathcal{P} := \{x \in \mathbb{R}^d \mid n_i \cdot x \geq b_i, \quad i = 1, \dots, m\}.$$

We assume that the interior of \mathcal{P} is nonempty and for each $j = 1, \dots, m$ we have:

$$(18) \quad \{x \in \mathbb{R}^d \mid n_i \cdot x \geq b_i, \quad i = 1, \dots, m, \quad i \neq j\} \neq \mathcal{P}.$$

In this case, the *edges* of \mathcal{P} :

$$\mathcal{P}_i = \{x \in \mathcal{P} \mid n_i \cdot x = b_i\}, \quad i = 1, \dots, m,$$

are $(d-1)$ -dimensional. Note that the vectors n_i , $i = 1, \dots, m$, are inward unit normal vectors to each of the faces $\mathcal{P}_1, \dots, \mathcal{P}_m$. Now, let us define an SRBM in the domain \mathcal{P} . Fix the parameters of this SRBM: a vector $\mu \in \mathbb{R}^d$, a $d \times d$ positive definite symmetric matrix A and a $d \times m$ -matrix R .

Definition 3.11. Fix a starting point $x \in \mathcal{P}$. Take $B = (B(t), t \geq 0)$ to be a d -dimensional Brownian motion with drift vector μ and covariance matrix A , starting from x . Take an adapted continuous \mathcal{P} -valued process $Z = (Z(t), t \geq 0)$ and an adapted continuous \mathbb{R}^m -valued process

$$L = (L(t), t \geq 0), \quad L(t) = (L_1(t), \dots, L_m(t))',$$

such that:

- (i) $Z(t) = B(t) + RL(t)$, $t \geq 0$;
- (ii) for every $i = 1, \dots, m$, $L_i(0) = 0$, L_i is nondecreasing and can increase only when $Z(t) \in \mathcal{P}_i$.

The process Z is called a *semimartingale reflected Brownian motion* (SRBM) in the domain \mathcal{P} with *reflection matrix* R , *drift vector* μ and *covariance matrix* A . This process is denoted by $\text{SRBM}^d(\mathcal{P}, R, \mu, A)$.

Remark 3.12. A particular case is an SRBM in the orthant S , which was introduced in Section 2: $\text{SRBM}^d(R, \mu, A)$ is the same as $\text{SRBM}^d(S, R, \mu, A)$.

Let v_i be the i th column of R . An $\text{SRBM}^d(\mathcal{P}, R, \mu, A)$ behaves as a d -dimensional Brownian motion with drift vector μ and covariance matrix A inside \mathcal{P} . On each face \mathcal{P}_i , it is reflected in the direction of the vector v_i .

The paper [14] contains an existence and uniqueness result for an SRBM in \mathcal{P} . We present this result in a slightly weaker version, which is still sufficient for this article. For any nonempty subset $I \subseteq \{1, \dots, m\}$, let $\mathcal{P}_I := \bigcap_{i \in I} \mathcal{P}_i$. A *positive linear combination* of vectors u_1, \dots, u_q is any vector $\alpha_1 u_1 + \dots + \alpha_q u_q$ with $\alpha_1, \dots, \alpha_q > 0$.

Assumption 3.13. For every nonempty subset $I \subseteq \{1, \dots, m\}$, we have:

- (i) $\mathcal{P}_I \neq \emptyset$ and $\mathcal{P}_J \subsetneq \mathcal{P}_I$ for $I \subsetneq J \subseteq \{1, \dots, m\}$;
- (ii) there is a positive linear combination v of vectors v_i , $i \in I$, such that $v \cdot n_i > 0$, $i \in I$;
- (iii) there is a positive linear combination n of vectors n_i , $i \in I$, such that $n \cdot v_i > 0$, $i \in I$.

The following result is an immediate corollary of [14, Theorem 1.3].

Proposition 3.14. *Under Assumption 3.13, for every $x \in \mathcal{P}$ there exists in the weak sense the process*

$$Z^{(x)} = (Z^{(x)}(t), t \geq 0) = \text{SRBM}^d(\mathcal{P}, R, \mu, A),$$

starting from $Z^{(x)}(0) = x$, and it is unique in law. This family of processes $(Z^{(x)}, x \in \mathcal{P})$ is Feller continuous strong Markov.

Remark 3.15. By Assumption 3.13(ii) applied to a subset $I = \{i\}$, we have: $v_i \cdot n_i > 0$. So we can normalize v_i to make $v_i \cdot n_i = 1$. This is done by replacing v_i by $k_i v_i$ for $k_i := (v_i \cdot n_i)^{-1}$ and replacing L_i by $k_i^{-1} L_i$. Doing this for each $i = 1, \dots, m$ is called *standard normalization*. The new reflection matrix is $\bar{R} = R\mathcal{D}$, where $\mathcal{D} = \text{diag}((v_1 \cdot n_1)^{-1}, \dots, (v_m \cdot n_m)^{-1})$. If $\bar{v}_i = k_i v_i$ is the i th column of \bar{R} , we can decompose it into the sum

$$(19) \quad \bar{v}_i = n_i + q_i,$$

where

$$q_i \cdot n_i = (\bar{v}_i - n_i) \cdot n_i = \bar{v}_i \cdot n_i - n_i \cdot n_i = 1 - 1 = 0, \quad i = 1, \dots, m.$$

These vectors n_i and q_i are called the *normal and tangential components* of the reflection vector \bar{v}_i , respectively. Similar normalization was done for an SRBM in the orthant in [6, Appendix B].

As mentioned above, in the papers [57], [58], [59], [61], [60], reflected Brownian motion was defined as a solution to a certain submartingale problem. We are going to show that if an SRBM is defined in a semimartingale form, as in Definition 3.11, then it is also a solution to this submartingale problem, so we can use the results of the papers mentioned above.

Definition 3.16. Take a convex polyhedron \mathcal{P} from (17) and the parameters R, μ, A from Definition 3.11. The symbol $C_c^2(\mathcal{P})$ stands for the family of twice continuously differentiable functions $f : \mathcal{P} \rightarrow \mathbb{R}$ with compact support. Define the following operator for functions $f \in C_c^2(\mathcal{P})$:

$$\mathcal{L}f := \frac{1}{2} \sum_{i=1}^d \sum_{j=1}^d a_{ij} \frac{\partial^2 f}{\partial x_i \partial x_j} + \sum_{i=1}^d \mu_i \frac{\partial f}{\partial x_i}.$$

A \mathcal{P} -valued continuous adapted process $Z = (Z(t), t \geq 0)$ is called a *solution to the submartingale problem associated with (\mathcal{P}, R, μ, A) , starting from $x \in \mathcal{P}$* , if:

- (i) $Z(0) = x$ a.s.;
- (ii) for every function $f \in C_c^2(\mathcal{P})$ which satisfies

$$v_i \cdot \nabla f(x) \geq 0 \quad \text{for } x \in \mathcal{P}_i, \quad \text{for each } i = 1, \dots, m,$$

the following process is an $(\mathcal{F}_t)_{t \geq 0}$ -submartingale:

$$\mathcal{M}^f = (\mathcal{M}^f(t), t \geq 0), \quad \mathcal{M}^f(t) = f(Z(t)) - \int_0^t \mathcal{L}f(Z(s)) ds.$$

Lemma 3.17. *The process $\text{SRBM}^d(\mathcal{P}, R, \mu, A)$, starting from $x \in \mathcal{P}$, is a solution to the submartingale problem associated with (\mathcal{P}, R, μ, A) , starting from x .*

The proof is postponed until the Appendix.

3.6. Connection between an SRBM in the orthant and an SRBM in a polyhedron.

Using the linear transformation (20), we can switch from an $\text{SRBM}^d(R, \mu, A)$ in the orthant with covariance matrix A to an SRBM^d in a convex polyhedron with identity covariance matrix.

Lemma 3.18. *Consider the process $Z = (Z(t), t \geq 0)$, which is an $\text{SRBM}^d(R, \mu, A)$. Define a new process $\bar{Z} = (\bar{Z}(t), t \geq 0)$ as follows:*

$$(20) \quad \bar{Z}(t) = A^{-1/2} Z(t).$$

- (i) *The process \bar{Z} is an $\text{SRBM}^d(\mathcal{P}, \bar{R}, \bar{\mu}, I_d)$ in the convex polyhedron*

$$(21) \quad \mathcal{P} := \{A^{-1/2} z \mid z \in S\} = \{\bar{z} \in \mathbb{R}^d \mid A^{1/2} \bar{z} \geq 0\},$$

with reflection matrix $\bar{R} := A^{-1/2}R$, drift vector $\bar{\mu} := A^{-1/2}\mu$ and covariance matrix $\bar{A} = I_d$. The domain \mathcal{P} is a convex polyhedron as in (17) with $m = d$ edges: $\mathcal{P}_i := \{A^{-1/2}x \mid x \in S_i\}$, $i = 1, \dots, d$. This domain satisfies the condition (18) and the Assumption 3.13 (i).

(ii) The standard normalization from Remark 3.15 gives us a new reflection matrix: $\tilde{R} := \bar{R}D^{1/2} = A^{-1/2}RD^{1/2}$. The i th column of \tilde{R} is equal to

$$(22) \quad v_i := a_{ii}^{1/2} A^{-1/2} R e_i, \quad i = 1, \dots, d.$$

The inward unit normal vector to the face \mathcal{P}_i is given by

$$(23) \quad n_i = a_{ii}^{-1/2} A^{1/2} e_i, \quad i = 1, \dots, d.$$

Furthermore, Assumption 3.13(ii) and (iii) is satisfied.

Proof. (i) We have: $Z(t) = B(t) + RL(t)$, where $B = (B(t), t \geq 0)$ is the driving Brownian motion for the process Z , and $L = (L(t), t \geq 0)$ is the vector of regulating processes. Here, B is a d -dimensional Brownian motion with drift vector μ and covariance matrix A . Define $W = (W(t), t \geq 0)$ as $W(t) = A^{-1/2}B(t)$: this is a d -dimensional Brownian motion with drift vector $\bar{\mu} = A^{-1/2}\mu$ and identity covariance matrix. Then $\bar{Z}(t) := A^{-1/2}Z(t) = W(t) + A^{-1/2}RL(t)$. The state space of \bar{Z} is the domain \mathcal{P} , given in (21). This is a convex polyhedron of the type (17). Let us show it satisfies the condition (18) and the Assumption 3.13 (i). The linear transformation (20) is a bijection $\mathbb{R}^d \rightarrow \mathbb{R}^d$, hence it suffices to show that the orthant S satisfies the condition (18) and the Assumption 3.13 (i), which is straightforward.

(ii) The face \mathcal{P}_i is spanned by vectors $A^{-1/2}e_j$, $j \in \{1, \dots, d\} \setminus \{i\}$. The vector n_i is normal to \mathcal{P}_i , so we must have: $n_i \cdot A^{-1/2}e_j = 0$. Since the matrix $A^{-1/2}$ is symmetric, $A^{-1/2}n_i \cdot e_j = 0$ for $j \in \{1, \dots, d\} \setminus \{i\}$. Therefore, $A^{-1/2}n_i = k_i e_i$ for some $k_i \in \mathbb{R}$; so $n_i = k_i A^{1/2}e_i$. Let us find k_i such that n_i is inward oriented and has unit length.

The inward orientation means that for any point w in the relative interior of the face \mathcal{P}_i , that is, in $\mathcal{P}_i \setminus (\cup_{j \neq i} \mathcal{P}_j)$, there exists $\varepsilon > 0$ such that $w + \varepsilon n_i \in \mathcal{P}$. But the domain \mathcal{P} is obtained from the orthant $S = \mathbb{R}_+^d$ by the linear transformation (20). So we have: $w = A^{-1/2}z$ for some z in the relative interior $S_i \setminus (\cup_{j \neq i} S_j)$ of the face S_i of ∂S . We must have $w + \varepsilon n_i \in \mathcal{P}$. But

$$w + \varepsilon n_i = A^{-1/2}(z + \varepsilon k_i A e_i), \quad \text{and} \quad \mathcal{P} = \{A^{-1/2}x \mid x \in S\}.$$

Therefore, $w + \varepsilon n_i \in \mathcal{P} \Leftrightarrow z + \varepsilon k_i A e_i \in S$. Since $z \in S_i$, we have: $z_i = 0$, and $(A e_i)_i = a_{ii} > 0$. But $z_i + \varepsilon k_i (A e_i)_i = (z + \varepsilon k_i A e_i)_i \geq 0$, so we must have: $k_i \geq 0$. Now, let us find $|k_i|$ using the fact that $\|n_i\| = 1$. Since the matrix $A^{1/2}$ is symmetric, we have:

$$\|A^{1/2}e_i\| = \left[A^{1/2}e_i \cdot A^{1/2}e_i \right]^{1/2} = \left[A^{1/2}(A^{1/2}e_i) \cdot e_i \right]^{1/2} = [A e_i \cdot e_i]^{1/2} = a_{ii}^{1/2}.$$

But $\|n_i\| = 1$, and $n_i = k_i A^{1/2}e_i$. So $|k_i| a_{ii}^{1/2} = 1$, and $|k_i| = a_{ii}^{-1/2}$. Earlier, we proved that $k_i \geq 0$. Therefore, $k_i = a_{ii}^{-1/2}$, which proves (23). Now, let us show (22). The i th column of $A^{-1/2}R$ is equal to $A^{-1/2}R e_i$. Using the fact that the matrix $A^{1/2}$ is symmetric, we have:

$$\begin{aligned} A^{-1/2}R e_i \cdot n_i &= A^{-1/2}R e_i \cdot a_{ii}^{-1/2} A^{1/2}e_i = a_{ii}^{-1/2} A^{1/2} A^{-1/2} R e_i \cdot e_i \\ &= a_{ii}^{-1/2} R e_i \cdot e_i = a_{ii}^{-1/2} r_{ii} = a_{ii}^{-1/2}. \end{aligned}$$

Therefore, the standard normalization defined in Remark 3.15 leads to

$$v_i := a_{ii}^{1/2} A^{-1/2} R e_i, \quad i = 1, \dots, d,$$

which proves (22). Now, let us show that the Assumption 3.13(ii) and (iii) is satisfied. Note that the matrix $A^{1/2}$ is symmetric, so for every $i, j = 1, \dots, d$ we have:

$$v_i \cdot n_j = a_{ii}^{1/2} a_{jj}^{-1/2} A^{-1/2} R e_i \cdot A^{1/2}e_j = a_{ii}^{1/2} a_{jj}^{-1/2} A^{1/2} A^{-1/2} R e_i \cdot e_j$$

$$= a_{ii}^{1/2} a_{jj}^{-1/2} R e_i \cdot e_j = a_{ii}^{1/2} a_{jj}^{-1/2} r_{ij}.$$

Fix a nonempty subset $I \subseteq \{1, \dots, d\}$ with $|I| = p$. Since the matrix R is completely- \mathcal{S} , the submatrix $[R]_I$ is an \mathcal{S} -matrix. There exist positive numbers α_i , $i \in I$, such that $\sum_{j \in I} r_{ij} \alpha_j > 0$ for $i \in I$. Take $n = \sum_{j \in I} a_{jj}^{1/2} \alpha_j n_j$. This is a positive linear combination of n_j , $j \in I$, and $v_i \cdot n = \sum_{j \in I} a_{ii}^{1/2} r_{ij} \alpha_j > 0$ for $i \in I$. This proves Assumption 3.13(iii). Similarly, the transposed matrix R' is also completely- \mathcal{S} (this follows from Lemma 2.5(ii)), so repeating this argument with R' in place of R , we can prove Assumption 3.13(ii). \square

3.7. Skew-symmetry condition. Consider a reflected Brownian motion in a general convex polyhedron in general dimension $d \geq 2$. Then a sufficient condition for a.s. not hitting non-smooth parts of the boundary is given by [61, Theorem 1.1]. It is called the *skew-symmetry condition*. In the subsequent exposition, we define this condition in (24), and show that it is equivalent (under the linear transformation (20)) to the skew-symmetry condition (13). This is the reason why these two conditions have the same name.

Definition 3.19. Consider an SRBM $^d(\mathcal{P}, R, \mu, A)$ with $\mu = 0$ and $A = I_d$. Suppose the matrix R is normalized, as described in Remark 3.15. We say that the *skew-symmetry condition* holds if

$$(24) \quad n_i \cdot q_j + n_j \cdot q_i = 0, \quad 1 \leq i, j \leq m.$$

This justifies the name of this condition: the matrix $(n_i \cdot q_j)_{1 \leq i, j \leq m}$ must be skew-symmetric.

We say that an SRBM $Z = (Z(t), t \geq 0)$ *hits non-smooth parts of the boundary* $\partial\mathcal{P}$ at time $t > 0$ if there exist $1 \leq i < j \leq m$ such that $Z(t) \in \mathcal{P}_i \cap \mathcal{P}_j$. This is a generalization of the concept of an SRBM in the orthant hitting non-smooth parts of the boundary. For an SRBM in a two-dimensional wedge, this is equivalent to hitting the corner of the wedge (the origin): a process $Z = (Z(t), t \geq 0)$ with values in this wedge *hits the corner* at time $t > 0$ if $Z(t) = 0$.

Proposition 3.20. *Under Assumption 3.13 and the skew-symmetry condition (24), an SRBM $^d(\mathcal{P}, R, \mu, A)$ starting from some point $x \in \mathcal{P} \setminus \partial\mathcal{P}$ in the interior of the polyhedral domain \mathcal{P} a.s. does not hit non-smooth parts of the boundary at any time $t > 0$.*

Proof. Follows from Lemma 3.17, Proposition 3.14 and [61, Theorem 1.1]. \square

The following lemma shows the equivalence of the two forms (13) and (24) of the skew-symmetry condition under the linear transformation (20).

Lemma 3.21. *Consider the process $Z = (Z(t), t \geq 0) = \text{SRBM}^d(R, \mu, A)$. Let \bar{Z} be the process defined by (20). Then the skew-symmetry condition in the form (13) holds for Z if and only if the skew-symmetry condition in the form (24) holds for \bar{Z} .*

Proof. Suppose (13) is true. Using (22), (23) and the fact that $v_i = n_i + q_i$, $i = 1, \dots, m$ (in this case $m = d$), we have:

$$\begin{aligned} n_i \cdot q_j + n_j \cdot q_i &= n_i \cdot (v_j - n_j) + n_j \cdot (v_i - n_i) = n_i \cdot v_j - n_j \cdot v_i - 2n_i \cdot n_j \\ &= a_{ii}^{-1/2} A^{1/2} e_i \cdot a_{jj}^{1/2} A^{-1/2} R e_j + a_{jj}^{-1/2} A^{1/2} e_j \cdot a_{ii}^{1/2} A^{-1/2} R e_i - 2a_{ii}^{-1/2} a_{jj}^{-1/2} A^{1/2} e_i \cdot A^{1/2} e_j. \end{aligned}$$

Since the matrix $A^{1/2}$ is symmetric, we have:

$$\begin{aligned} a_{ii}^{-1/2} A^{1/2} e_i \cdot a_{jj}^{1/2} A^{-1/2} R e_j &= a_{ii}^{-1/2} a_{jj}^{1/2} \left(e_i \cdot A^{1/2} A^{-1/2} R e_j \right) \\ &= a_{ii}^{-1/2} a_{jj}^{1/2} (e_i \cdot R e_j) = a_{ii}^{-1/2} a_{jj}^{1/2} r_{ij}, \end{aligned}$$

similarly

$$a_{jj}^{-1/2} A^{1/2} e_j \cdot a_{ii}^{1/2} A^{-1/2} R e_i = a_{jj}^{-1/2} a_{ii}^{1/2} r_{ji},$$

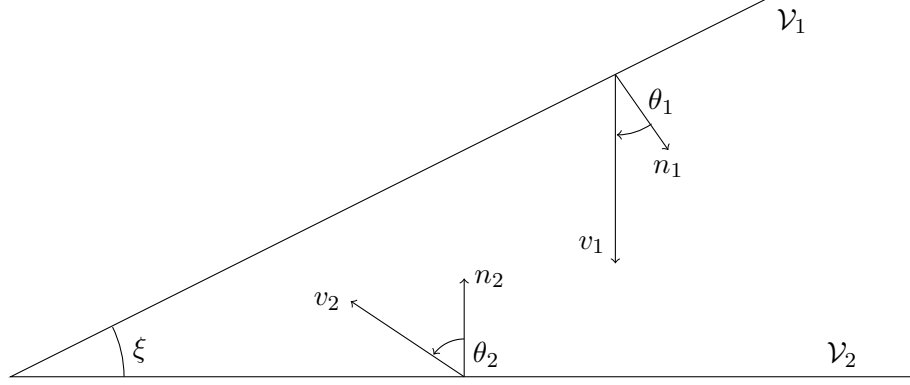


FIGURE 1. A two-dimensional wedge.

Angles θ_1 and θ_2 are counted toward the vertex of the wedge

Here, n_1 and n_2 are normal vectors, v_1 and v_2 are reflection vectors

and finally

$$\begin{aligned} a_{ii}^{-1/2} a_{jj}^{-1/2} A^{1/2} e_i \cdot A^{1/2} e_j &= a_{ii}^{-1/2} a_{jj}^{-1/2} (e_i \cdot A^{1/2} A^{1/2} e_j) \\ &= a_{ii}^{-1/2} a_{jj}^{-1/2} (e_i \cdot A e_j) = a_{ii}^{-1/2} a_{jj}^{-1/2} a_{ij}. \end{aligned}$$

Therefore,

$$\begin{aligned} n_i \cdot q_j + n_j \cdot q_i &= a_{ii}^{-1/2} a_{jj}^{1/2} r_{ij} + a_{jj}^{-1/2} a_{ii}^{1/2} r_{ji} - 2a_{ii}^{-1/2} a_{jj}^{-1/2} a_{ij} \\ &= a_{ii}^{-1/2} a_{jj}^{-1/2} [r_{ij} a_{jj} + r_{ji} a_{ii} - 2a_{ij}] = 0. \end{aligned}$$

The converse statement is proved similarly. \square

3.8. An SRBM in a two-dimensional wedge. A particular case of a polyhedral domain is a *two-dimensional wedge* (see Fig. 1), considered in [57], [58], [59], [60]:

$$\mathcal{V} := \{(r \cos \theta, r \sin \theta) \mid 0 \leq r < \infty, \xi_2 \leq \theta \leq \xi_1\}.$$

Here, $\xi_2 < \xi_1 < \xi_2 + \pi$. Its *angle* is defined as $\xi := \xi_1 - \xi_2$. Its boundary $\partial\mathcal{V}$ consists of two edges

$$\mathcal{V}_i := \{(r \cos \xi_i, r \sin \xi_i) \mid 0 \leq r < \infty\}, \quad i = 1, 2.$$

The edge \mathcal{V}_1 is called the *upper edge*, and the edge \mathcal{V}_2 is called the *lower edge*. The difference between them is as follows: the shorter way to rotate \mathcal{V}_1 to get \mathcal{V}_2 is clockwise rather than counterclockwise. On each edge \mathcal{V}_i , there is a reflection vector v_i , which forms the angle $\theta_i \in (-\pi/2, \pi/2)$ with the inward unit normal vector n_i .

These angles are signed: positive angles θ_1, θ_2 are measured toward the vertex of \mathcal{V} (the origin). In other words, θ_1 is the angle between n_1 and v_1 , measured clockwise in the direction from n_1 to v_1 . This means the following: if the shorter way to rotate the direction of n_1 to get the direction of v_1 is clockwise, then $\theta_1 > 0$; and if it is counterclockwise, then $\theta_1 < 0$. If v_1 and n_1 have the same direction, then $\theta_1 = 0$. Similarly, θ_2 is the angle between n_2 and v_2 , measured counterclockwise from n_2 to v_2 .

We are interested in whether a reflected Brownian motion with zero drift vector and identity covariance matrix in this wedge hits the corner. A necessary and sufficient condition is established in [57, Theorem 2.2].

Proposition 3.22. *Consider an SRBM $Z = (Z(t), t \geq 0)$ in the wedge \mathcal{V} with $\mu = 0$ and $A = I_2$, starting from a point $x \in \mathcal{V} \setminus \partial\mathcal{V}$.*

(i) *If $\theta_1 + \theta_2 > 0$, then a.s. there exists $t > 0$ such that $Z(t) = 0$.*

(ii) *If $\theta_1 + \theta_2 \leq 0$, then a.s. there does not exist $t > 0$ such that $Z(t) = 0$.*

Proof. Follows from Lemma 3.17, Proposition 3.14, and Theorem 2.2 from [57]. \square

In the case of two dimensions, $d = 2$, the linear transformation (20) leads to an SRBM in a two-dimensional wedge with identity covariance matrix. In the following lemma, we explicitly calculate the parameters of this SRBM: the angle ξ of this wedge and the two angles θ_1, θ_2 of reflection.

Lemma 3.23. *Suppose $Z = \text{SRBM}^2(R, 0, A)$ and \bar{Z} is the process defined by (20). Then the polyhedral domain \mathcal{P} is in fact a wedge \mathcal{V} with the angle*

$$(25) \quad \xi = \arccos \left[-\frac{a_{12}}{\sqrt{a_{11}a_{22}}} \right].$$

The process \bar{Z} is an SRBM in \mathcal{V} with zero drift vector, identity covariance matrix and the angles of reflection

$$(26) \quad \theta_1 = \arcsin \frac{a_{12} - a_{11}r_{21}}{\sqrt{a_{11}(a_{11}r_{21}^2 - 2a_{12}r_{21} + a_{22})}},$$

$$(27) \quad \theta_2 = \arcsin \frac{a_{12} - a_{22}r_{12}}{\sqrt{a_{22}(a_{22}r_{12}^2 - 2a_{12}r_{12} + a_{11})}}.$$

Proof. First, note that $A^{-1/2}$ is a positive definite matrix, so it has a positive determinant. Therefore, the linear transformation (20) preserves the orientation of the plane \mathbb{R}_+^2 . The edges of this wedge are

$$\mathcal{V}_i := A^{-1/2}S_i \equiv \{A^{-1/2}z \mid z \in S_i\}, \quad i = 1, 2.$$

In fact, \mathcal{V}_1 is the upper edge, and \mathcal{V}_2 is the lower edge. Indeed, for the original quadrant $S = \mathbb{R}_+^2$, the edge $S_1 = \{x \in S \mid x_1 = 0\}$ is the upper edge, and the edge $S_2 = \{x \in S \mid x_2 = 0\}$ is the lower edge: in other words, the shorter way to rotate S_1 to get S_2 is clockwise rather than counterclockwise. But under the transformation 14, S_1 is mapped to \mathcal{V}_1 , and S_2 is mapped to \mathcal{V}_2 . This linear transformation preserves the orientation. Therefore, the shorter way to rotate \mathcal{V}_1 to get \mathcal{V}_2 is also clockwise rather than counterclockwise. The edge \mathcal{V}_1 has a directional vector $c_2 = A^{-1/2}e_2$, while the edge \mathcal{V}_2 has a directional vector $c_1 = A^{-1/2}e_1$. An important remark: consider the notation \mathcal{P}_i , $i = 1, \dots, d$, for edges of the polyhedron from Lemma 3.18. Then our current notation \mathcal{V}_1 and \mathcal{V}_2 is consistent with this notation in the sense that

$$(28) \quad \mathcal{V}_1 = \mathcal{P}_1 \quad \text{and} \quad \mathcal{V}_2 = \mathcal{P}_2.$$

The angle ξ of the wedge is the angle between the edges \mathcal{V}_1 and \mathcal{V}_2 . So ξ is the angle between two vectors $c_1 = A^{-1/2}e_1$ and $c_2 = A^{-1/2}e_2$. Since the matrix $A^{-1/2}$ is symmetric, we have:

$$\begin{aligned} \cos \xi &= \frac{A^{-1/2}e_1 \cdot A^{-1/2}e_2}{\|A^{-1/2}e_1\| \|A^{-1/2}e_2\|} = \frac{(A^{-1/2})^2 e_1 \cdot e_2}{[(A^{-1/2})^2 e_1 \cdot e_1]^{1/2} [(A^{-1/2})^2 e_2 \cdot e_2]^{1/2}} \\ &= \frac{A^{-1}e_1 \cdot e_2}{[A^{-1}e_1 \cdot e_1]^{1/2} [A^{-1}e_2 \cdot e_2]^{1/2}} = \frac{(A^{-1})_{12}}{(A^{-1})_{11}^{1/2} (A^{-1})_{22}^{1/2}}. \end{aligned}$$

But

$$(29) \quad A^{-1} = \frac{1}{a_{11}a_{22} - a_{12}^2} \begin{bmatrix} a_{22} & -a_{12} \\ -a_{12} & a_{11} \end{bmatrix}$$

Therefore,

$$\cos \xi = -\frac{a_{12}}{\sqrt{a_{11}a_{22}}},$$

and we get (25). Let us find the reflection angles θ_1 and θ_2 . For the quadrant $S = \mathbb{R}_+^2$, if we rotate the directional vector e_2 of the upper face S_1 clockwise by $\pi/2$, we get an inward normal vector to this face. But the linear transformation (20) preserves the orientation, so a similar statement is true for the wedge \mathcal{V} : if we rotate the directional vector $c_2 = A^{-1/2}e_2$ of the upper face \mathcal{V}_1 of the wedge clockwise by $\pi/2$, then we get an inward normal vector

$$\mathbf{n}_1 \equiv \begin{bmatrix} (\mathbf{n}_1)_1 \\ (\mathbf{n}_1)_2 \end{bmatrix} := \begin{bmatrix} (c_2)_2 \\ -(c_2)_1 \end{bmatrix}$$

Similarly, if we rotate the vector $c_1 = A^{-1/2}e_1$ by $\pi/2$ counterclockwise, we get an inward normal vector

$$\mathbf{n}_2 \equiv \begin{bmatrix} (\mathbf{n}_2)_1 \\ (\mathbf{n}_2)_2 \end{bmatrix} := \begin{bmatrix} -(c_1)_2 \\ (c_1)_1 \end{bmatrix}$$

to \mathcal{V}_1 . These are not unit vectors: $\mathbf{n}_i \neq n_i$. In fact, $\|\mathbf{n}_1\| = \|c_2\|$ and $\|\mathbf{n}_2\| = \|c_1\|$. But \mathbf{n}_1 has the same direction as n_1 , and \mathbf{n}_2 has the same direction as n_2 . In other words, $\mathbf{n}_1 = \|\mathbf{n}_1\|n_1$ and $\mathbf{n}_2 = \|\mathbf{n}_2\|n_2$.

From Lemma 3.18 and (28), it follows that $v_1 = A^{-1/2}r_1$ and $v_2 = A^{-1/2}r_2$. These vectors are *not normalized* in the sense of Remark 3.15. The angle θ_1 between n_1 and v_1 has a sign: it is calculated toward the origin, or, in other words, counterclockwise from n_1 to v_1 . But n_1 and \mathbf{n}_1 have the same direction. Therefore, θ_1 can be calculated as the signed angle from \mathbf{n}_1 to v_1 in the counterclockwise direction:

$$\begin{aligned} \sin \theta_1 &= \frac{(\mathbf{n}_1)_1(v_1)_2 - (\mathbf{n}_1)_2(v_1)_1}{\|\mathbf{n}_1\|\|v_1\|} = \frac{-(c_2)_2(v_1)_2 - (c_2)_1(v_1)_1}{\|c_2\|\|v_1\|} = -\frac{c_2 \cdot v_1}{\|c_2\|\|v_1\|} \\ &= -\frac{A^{-1/2}e_2 \cdot A^{-1/2}r_1}{\|A^{-1/2}e_2\|\|A^{-1/2}r_1\|} = -\frac{A^{-1/2}e_2 \cdot A^{-1/2}r_1}{[A^{-1/2}e_2 \cdot A^{-1/2}r_1]^{1/2} [A^{-1/2}e_2 \cdot A^{-1/2}r_1]^{1/2}} \end{aligned}$$

Since the matrix $A^{-1/2}$ is symmetric, the last expression is equal to

$$-\frac{A^{-1}e_2 \cdot r_1}{[A^{-1}e_2 \cdot e_2]^{1/2} [A^{-1}r_1 \cdot r_1]^{1/2}}.$$

Using the formula (29) for A^{-1} and the fact that $r_1 = (1, r_{21})'$, we have:

$$\sin \theta_1 = \frac{a_{12} - a_{11}r_{21}}{\sqrt{a_{11}(a_{11}r_{21}^2 - 2a_{12}r_{21} + a_{22})}}.$$

Similarly, we can calculate the angle θ_2 :

$$\sin \theta_2 = \frac{a_{12} - a_{22}r_{12}}{\sqrt{a_{22}(a_{22}r_{12}^2 - 2a_{12}r_{12} + a_{11})}}.$$

Since $\theta_1, \theta_2 \in (-\pi/2, \pi/2)$, we get (26) and (27). \square

3.9. Completion of the proof of Theorem 2.12. By Lemma 3.6, without loss of generality we can assume an SRBM starts from some point $x \in S \setminus \partial S$, and $\mu = 0$. First, we prove (i) in the case of the skew-symmetry condition (13), then move to the general case (12). Then we prove (ii) in the case $d = 2$, and proceed to the case of the general dimension.

Lemma 3.24. *Take an SRBM in the orthant S , starting from $x \in S \setminus \partial S$. Suppose it satisfies the skew-symmetry condition (13). Then the statement of Theorem 2.12(i) is true.*

Proof. Apply the linear transformation (20) to $Z = (Z(t), t \geq 0) = \text{SRBM}^d(R, 0, A)$. By Lemma 3.18, we get an SRBM $\bar{Z} = (\bar{Z}(t), t \geq 0)$ in the polyhedron $\mathcal{S} = A^{-1/2}S$, given by (21) with zero drift and identity covariance matrix. It was shown in Lemma 3.21 that the skew-symmetry condition (24) is true. Therefore, by Proposition 3.20 the process \bar{Z} a.s. does not hit non-smooth parts of the boundary $\partial\mathcal{S}$ at any moment $t > 0$. Thus, the process Z a.s. does not hit non-smooth parts of the boundary ∂S at any moment $t > 0$. \square

Lemma 3.25. *Take an SRBM in the orthant S , starting from $x \in S \setminus \partial S$. Suppose it satisfies the condition (12). Then the statement of Theorem 2.12(i) is true.*

Proof. Let us find another reflection nonsingular \mathcal{M} -matrix $\tilde{R} = (\tilde{r}_{ij})_{1 \leq i, j \leq d}$ such that $R \geq \tilde{R}$, and the skew-symmetry condition (13) is true for an SRBM $^d(\tilde{R}, 0, A)$. We need:

$$(30) \quad \tilde{r}_{ij}a_{jj} + \tilde{r}_{ji}a_{ii} = 2a_{ij}, \quad i, j = 1, \dots, d.$$

Let $\tilde{r}_{ij} = 1$ for $i = j$. Then (30) is true for $i = j$. Let

$$\tilde{r}_{ij} = \frac{1}{a_{jj}} [2a_{ij} - r_{ji}a_{ii}], \quad \tilde{r}_{ji} = r_{ji}, \quad 1 \leq i < j \leq d.$$

This is well defined, since $a_{jj} > 0$ (because the matrix A is positive definite). Also, $\tilde{r}_{ij} \leq r_{ij}$, because $r_{ij}a_{jj} + r_{ji}a_{ii} \geq 2a_{ij}$. Since $\tilde{r}_{ij} \leq r_{ij} \leq 0$ for $i \neq j$, \tilde{R} is a \mathcal{Z} -matrix, so condition (30) holds. Therefore, by [30, Theorem 2.5] (compare conditions 12 and 16), \tilde{R} is a nonsingular \mathcal{M} -matrix. Consider two processes $Z = \text{SRBM}^d(R, \mu, A)$, $\tilde{Z} = \text{SRBM}^d(\tilde{R}, \mu, A)$, starting from the same initial condition $x \in S \setminus \partial S$. Then we have: R and \tilde{R} are $d \times d$ reflection nonsingular \mathcal{M} -matrices, and $R \geq \tilde{R}$. By Proposition 3.9, we have: \tilde{Z} is stochastically smaller than Z . By [35, Theorem 5], we can claim that a.s. for all $t > 0$ we have: $\tilde{Z}(t) \leq Z(t)$ (possibly after changing the probability space). By Lemma 3.24, the process \tilde{Z} a.s. does not hit non-smooth parts of the boundary at any time $t > 0$. In other words, for every $1 \leq i < j \leq d$, we have: a.s. $\tilde{Z}_i(t) + \tilde{Z}_j(t) > 0$ for all $t > 0$. Therefore, a.s. $Z_i(t) + Z_j(t) > 0$ for all $t > 0$. Thus, with probability one the process Z does not hit non-smooth parts of the boundary at any time $t > 0$. \square

Now, let us prove part (ii) of Theorem 2.12. We start with the case $d = 2$, then move to the general case.

Lemma 3.26. *Suppose we start an SRBM in two dimensions from a point $x \in S \setminus \partial S$ in the interior of S . Then the statement of Theorem 2.12 (ii) is valid.*

Proof. Let $Z = (Z(t), t \geq 0) = \text{SRBM}^2(R, 0, A)$. After the linear transformation (20), we get the process $\bar{Z} = (\bar{Z}(t), t \geq 0)$ from (20), which is an SRBM in a wedge. If we show that $\theta_1 + \theta_2 > 0$, then by Lemma 3.22 we have: a.s. there exists $t > 0$ such that $\bar{Z}(t) \equiv A^{-1/2}Z(t) = 0$; therefore, a.s. there exists $t > 0$ such that $Z(t) = 0$. But the angles θ_1, θ_2 are given in the equations (26) and (27). Since $\theta_1, \theta_2 \in (-\pi/2, \pi/2)$, we have:

$$\theta_1 + \theta_2 > 0 \quad \Leftrightarrow \quad \sin \theta_1 + \sin \theta_2 > 0,$$

which can be written as

$$(31) \quad \frac{a_{11}r_{21} - a_{12}}{\sqrt{a_{11}(a_{11}r_{21}^2 - 2a_{12}r_{21} + a_{22})}} + \frac{a_{22}r_{12} - a_{12}}{\sqrt{a_{22}(a_{22}r_{12}^2 - 2a_{12}r_{12} + a_{11})}} < 0.$$

Then we have:

$$r'_{12} := a_{11}^{-1/2} a_{22}^{1/2} r_{12}, \quad r'_{21} = a_{11}^{1/2} a_{22}^{-1/2} r_{21}, \quad \rho := a_{11}^{-1/2} a_{22}^{-1/2} a_{12}.$$

We can rewrite the condition (31) as

$$\frac{r'_{12} - \rho}{\sqrt{(r'_{12})^2 - 2\rho r'_{12} + 1}} + \frac{r'_{21} - \rho}{\sqrt{(r'_{21})^2 - 2\rho r'_{21} + 1}} < 0.$$

Or, equivalently, $f(r'_{12} - \rho) + f(r'_{21} - \rho) < 0$, where

$$f(x) := \frac{x}{\sqrt{x^2 + 1 - \rho^2}}.$$

Note that the matrix A is positive definite, so $\det A = a_{11}a_{22} - a_{12}^2 > 0$. Therefore, $\rho^2 < 1$. It is easy to show that the function f is strictly increasing on \mathbb{R} . In addition, this function is odd: $f(x) + f(-x) \equiv 0$. Therefore, $f(r'_{12} - \rho) + f(r'_{21} - \rho) < 0$ is equivalent to

$$(r'_{12} - \rho) + (r'_{21} - \rho) < 0 \Leftrightarrow r_{12}a_{22} + r_{21}a_{11} < 2a_{12}.$$

□

Lemma 3.27. *The statement (ii) of Theorem 2.12 is valid in the case of general dimension, if we start an SRBM from a point $x \in S \setminus \partial S$ in the interior of S .*

Proof. Let $Z = \text{SRBM}^d(R, 0, A)$. Assume now that the condition (12) is not true, and for some $1 \leq i < j \leq d$ we have:

$$(32) \quad r_{ij}a_{jj} + r_{ji}a_{ii} < 2a_{ij}.$$

Consider the following two-dimensional SRBM: $\tilde{Z} = \text{SRBM}^2([R]_I, 0, [A]_I)$, where $I = \{i, j\}$. Applying Corollary 3.10 to $I := \{i, j\}$, we get: $[Z]_I \preceq \tilde{Z}$. By [35, Theorem 5], we can switch from stochastic comparison to pathwise comparison: after changing the probability space, we can claim that a.s. for all $t > 0$ we have: $[Z(t)]_I \leq \tilde{Z}(t)$. By Lemma 3.26, with positive probability, there exists $t > 0$ such that $\tilde{Z}_i(t) = \tilde{Z}_j(t) = 0$. Therefore, with positive probability there exists $t > 0$ such that $Z_i(t) = Z_j(t) = 0$. □

4. PROOF OF THEOREMS 1.4 AND 1.9

Theorem 1.9 can be easily deduced from Theorem 2.12. First, let us prove part (i) of Theorem 1.9. We need to rewrite the condition (12) for concrete matrices R and A arising from competing Brownian particles, given by (8) and (9). Take $i, j = 1, \dots, N - 1$ and consider the condition

$$(33) \quad r_{ij}a_{jj} + r_{ji}a_{ii} \geq 2a_{ij}.$$

If $i = j$, then (33) is always true, because for such i, j we have: $r_{ij} = r_{ji} = 1$, and $a_{ii} = a_{ij} = a_{jj} = \sigma_i^2 + \sigma_{i+1}^2$. If $|i - j| \geq 2$, then (33) is also always true, since $r_{ij} = r_{ji} = a_{ij} = 0$. Since the left-hand side and the right-hand side of (33) remain the same if we swap i and j , we need only to check this condition for $j = k, i = k - 1$, where $k = 2, \dots, N - 1$. We get:

$$r_{ij} = -q_k^-, \quad r_{ji} = -q_k^+, \quad a_{jj} = \sigma_k^2 + \sigma_{k+1}^2, \quad a_{ii} = \sigma_{k-1}^2 + \sigma_k^2, \quad a_{ij} = -\sigma_k^2.$$

Therefore, the condition (33) takes the form

$$-q_k^- (\sigma_k^2 + \sigma_{k+1}^2) - q_k^+ (\sigma_{k-1}^2 + \sigma_k^2) \geq -2\sigma_k^2.$$

This is equivalent to

$$(34) \quad (2 - q_k^- - q_k^+) \sigma_k^2 \geq q_k^- \sigma_{k+1}^2 + q_k^+ \sigma_{k-1}^2.$$

Note that $q_k^- + q_{k+1}^+ = 1$ and $q_k^+ + q_{k-1}^- = 1$. Therefore, we can rewrite (34) as in (7). This proves part (i) of Theorem 1.9. Now, let us prove part (ii) of this theorem. Since the condition (12) is automatically valid for $i = j$ and for $|i - j| \geq 2$, it can be violated only for $i = j - 1$. Suppose it

does not hold for $j = k$ and $i = k - 1$, where $k = 2, \dots, N - 1$ is some index. Then with positive probability, there exists $t > 0$ such that

$$Z_{k-1}(t) = Z_k(t) = 0,$$

which can be written as

$$Y_{k-1}(t) = Y_k(t) = Y_{k+1}(t).$$

This means that with positive probability, there is a triple collision between particles with ranks $k - 1$, k and $k + 1$. This completes the proof of Theorem 1.9.

Theorem 1.4 is simply a corollary of Theorem 1.9: just plug parameters of collision $q_k^\pm = 1/2$, $k = 1, \dots, N$ into the inequality (7).

Remark 4.1. Let us explain the meaning of Corollary 1.5 informally. Consider the gap process of a system of competing Brownian particles from Definition 1.6. This is an SRBM $Z = (Z(t), t \geq 0)$ in the orthant with reflection matrix R and covariance matrix A , given by (8) and (9). In this case, the condition (12) can be violated only for $i = j - 1$, because for $i = j$ and $|i - j| \geq 2$ it is automatically true.

When $Z_i(t) = Z_j(t) = 0$ for $1 \leq i < j \leq d$, this corresponds to a simultaneous collision at time t in this system of competing Brownian particles: $Y_i(t) = Y_{i+1}(t)$ and $Y_j(t) = Y_{j+1}(t)$. But if, in addition, we know that $i = j - 1$, then this is a particular case of a simultaneous collision: namely, a *triple collision* between particles with ranks $j - 1$, j and $j + 1$. This implies that if the condition (12) does not hold, then with positive probability there occurs a simultaneous collision of a special kind: a triple collision. This is the reason why Corollary 1.5 is true.

5. APPENDIX

5.1. Proof of Lemma 2.5. (i) \Rightarrow (iii). Use [30, Theorem 2.5.3]. Since R is completely- \mathcal{S} , it satisfies condition 12 from this theorem. Therefore, it satisfies condition 2 from this theorem. We get the following representation: $R = \gamma I_d - Q$, where $\gamma := \max_{1 \leq i \leq d} r_{ii} = 1$, and a $d \times d$ -matrix Q is nonnegative with spectral radius less than one. (See the beginning of [30, Section 2.5.4].)

(iii) \Rightarrow (ii). By [44, Section 7.10], we can represent R^{-1} as Neumann series:

$$R^{-1} = I_d + Q + Q^2 + \dots$$

Since Q is nonnegative, R^{-1} is also nonnegative, and the diagonal elements of R^{-1} are strictly positive (and even greater than or equal to 1).

(ii) \Rightarrow (i). Apply [30, Theorem 2.5.3] again: condition 17 implies condition 12. Therefore, there exists $x \in \mathbb{R}^d$, $x > 0$ such that $Rx > 0$, so R is an \mathcal{S} -matrix. Take a principal submatrix \tilde{R} of R and show that it is also an \mathcal{S} -matrix. Let $\tilde{R} := [R]_I$, where $I \subsetneq \{1, \dots, d\}$ is a nonempty set. Let $\tilde{x} := [x]_I$. Then $r_{ij} \leq 0$ for $i \in I$ and $j \in I^c := \{1, \dots, d\} \setminus I$, and

$$(\tilde{R}\tilde{x})_i = \sum_{j \in I} r_{ij}x_j \geq \sum_{i=1}^d r_{ij}x_j = (Rx)_i > 0, \quad i \in I.$$

Therefore, $\tilde{x} > 0$ and $\tilde{R}\tilde{x} > 0$. So every principal submatrix of R is an \mathcal{S} -matrix, which proves that the matrix R is completely- \mathcal{S} .

5.2. Proof of Lemma 3.17. Recall that the process $Z = (Z(t), t \geq 0)$ which is an SRBM $^d(\mathcal{P}, R, \mu, A)$ can be represented as $Z(s) = B(t) + RL(t)$. Here, $B = (B(t), t \geq 0)$ is a d -dimensional Brownian motion with drift vector μ and covariance matrix $A = (a_{ij})_{1 \leq i, j \leq d}$; $R = (r_{ij})$ is an $m \times d$ -matrix, and $L = (L_1, \dots, L_m)'$, where each L_i is nondecreasing. Therefore, the mutual variation of the components of Z is calculated as follows: $\langle Z_i, Z_j \rangle_t = a_{ij}t$, for $i, j = 1, \dots, d$. The process

$(B_i(s) - \mu_i s, s \geq 0)$ is a one-dimensional driftless Brownian motion. Since $f \in C_c^2(\mathcal{P})$, the following process is a martingale:

$$M(t) = \sum_{i=1}^d \int_0^t \frac{\partial f}{\partial x_i}(Z(s)) d(B_i(s) - \mu_i s).$$

Apply the Itô-Tanaka formula to $f(Z(t))$:

$$\begin{aligned} f(Z(t)) - f(Z(0)) &= \sum_{i=1}^d \int_0^t \frac{\partial f}{\partial x_i}(Z(s)) dZ(s) + \frac{1}{2} \sum_{i=1}^d \sum_{j=1}^d \int_0^t \frac{\partial^2 f}{\partial x_i \partial x_j}(Z(s)) d\langle Z_i, Z_j \rangle_s \\ &= \sum_{i=1}^d \int_0^t \frac{\partial f}{\partial x_i}(Z(s)) d(B_i(s) - \mu_i s) + \sum_{i=1}^d \int_0^t \frac{\partial f}{\partial x_i}(Z(s)) \mu_i ds \\ &\quad + \frac{1}{2} \sum_{i=1}^d \sum_{j=1}^d a_{ij} \int_0^t \frac{\partial^2 f}{\partial x_i \partial x_j}(Z(s)) ds + \sum_{i=1}^d \int_0^t \frac{\partial f}{\partial x_i}(Z(s)) d \left[\sum_{j=1}^m r_{ij} L_j(s) \right] \\ &= M(t) + \int_0^t \mathcal{L}f(Z(s)) ds + \sum_{i=1}^d \sum_{j=1}^m \int_0^t r_{ij} \frac{\partial f}{\partial x_i}(Z(s)) dL_j(s) \\ &= M(t) + \int_0^t \mathcal{L}f(Z(s)) ds + \sum_{j=1}^m \int_0^t v_j \cdot \nabla f(Z(s)) dL_j(s). \end{aligned}$$

The third term in the last sum is nondecreasing. Indeed, for each $j = 1, \dots, m$, the process L_j is nondecreasing, and it can increase only when $Z(s) \in \mathcal{P}_j$. But in this case, $v_j \cdot \nabla f(Z(s)) \geq 0$. The rest is trivial.

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