Quizzing active matter: one's ability to solve a maze depends on one's behaviour

Active Brownian particles and run-and-tumble particles separate inside a maze
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Reference: Scientific Reports **6**, Article No: 37670 (2016) [doi:10.1038/srep37670]

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The pattern of stochastic movement of motile particles, objects, agents, and beings, affects their efficiency when they aim towards specific targets, say when animals search for food [1]. A quantitative measure of this efficiency, namely the mean first passage time (MFPT), can be minimized for a given search over specific classes of motility patterns, and it is often the case, though not always, that a pattern of straight runs that are randomized with sudden tumble events is the most efficient [2]. While for an electron moving in a lattice according to a Drude model the pattern of motility is not a matter of choice, we often tend to think of this pattern as a basic representation of behaviour when we are thinking of animals, say in the context of foraging or predator-prey dynamics. These two extreme limits of the spectrum—"determinism" of the governing rule for inanimate objects and "free will" to choose for animates—have traditionally been the way we have perceived and classified motility behaviour in matter. However, very primitive forms of life such as bacteria have the ability to exhibit different kinds of motility patterns depending on the circumstances, and this has inspired recent research in active matter, which aims to make artificial microscopic systems with such abilities.

There are two commonly used paradigms for the motility pattern of self-propelled particles: the Run-and-Tumble Particle (RTP) model described above that has been mostly used to study bacterial dynamics [3] and the Active Brownian Particle (ABP) model, which represents a colloidal system with an intrinsic self-propulsion mechanism (such as the catalytic Janus particle [4]). Although these two different motility behaviours look different to the eye, they do not belong to different universality classes in the sense that statistical probes extracted from moments of their distributions are equivalent. In a recent work, Maryam Khatami *et al.* [5] have asked a very interesting question: what happens if a self-propelled particle is challenged to solve a maze? Will there be a difference in how the ABP and the RTP attempt the challenge and their abilities to succeed? The answer is yes.

Khatami and collaborators probe the effects of wall curvature (by considering two different maze geometries: square and circular), architecture (by considering random versus regular connectivities), and initial and final positions (by considering both inward and outward searches). ABP appears to be moderately more efficient in solving the maze when it is initially placed at the centre and the task is to go outwards, whereas RTP is significantly more efficient in solving the maze inwards from an outer shell initial position; indeed the MFPT diverges for the ABP when the motion is significantly persistent, which means that essentially it cannot do it. How can we understand this? Consider a particle with self-propulsion speed v_0 along a body axis $\mathbf{n}(t)$. If $\mathbf{n}(t)$ undergoes a stochastic process then the trajectory of the particle $\mathbf{r}(t)$ will be stochastic, and the pattern will be determined by the type of stochastic process we assume for $\mathbf{n}(t)$: a smooth rotational Brownian motion will give us an ABP and a Poisson process in which we randomize $\mathbf{n}(t)$ by a finite rotation after a random period of time will give us a RTP. If the particle is moving in a potential landscape $U(\mathbf{r})$ (with mobility μ), we can observe that the stochastic equation of motion

$$\frac{\mathrm{d}}{\mathrm{dt}}\,\mathbf{r}(t) = v_0\,\mathbf{n}(t) - \mu\nabla U(\mathbf{r}(t)), \tag{1}$$

predicts that the particle spends a lot of time pointing in the direction of the gradient of the potential

$$\big\langle \mathbf{n}(t)\big\rangle \sim \mu\big\langle \nabla U(\mathbf{r}(t))\big\rangle / v_0. \tag{2}$$

If the potential landscape consists of a maze of impenetrable walls, the particle will polarize and invest most of its time on the futile quest to penetrate the walls. Now, the pattern of the residual movement parallel to the walls caused by fluctuations will be inherited from the motility pattern, which determines the stochastic dynamics of $\mathbf{n}(t)$. An RTP will move like a loose cannon, and will miss out on the fine search for openings between the different shells, whereas for ABP the lateral search in any neighbourhood will have more finesse and can lead to the openings more efficiently. Based on this argument, we expect these differences to be washed out in a randomized maze for sufficiently long trajectories, which is indeed what they observe. The asymmetry between inward and outward can be understood by considering the effect of wall curvature on the stability of the particle based on Eq. (2): when the particle is trying to penetrate an inner shell ($\mathbf{n}(t)$ opposite the surface normal vector), it is relatively easier for it to escape than when it is trying to penetrate an outer shell ($\mathbf{n}(t)$ along the surface normal vector). This feature also explains the predominantly quantitative (and not qualitative) difference observed between the square and the circular mazes.

The work by Khatami *et al.* provides a remarkable starting point for a new line of investigation in the field of active matter: now that it is established that we can make colloidal systems that exhibit motility like bacteria, it is time to investigate how these artificial microscopic systems can exhibit other bacteria-like behaviours, which might appear beyond reach at first. For example, it has emerged recently that trail-following surface-motile bacteria can use a peculiar tendency to align perpendicularly to their own tracks to modify their search strategy from thorough and local to far-reaching by changing a single parameter, namely the rate of polysaccharide deposition [6]. We should be able to make artificial self-propelled particles that can achieve such control over their search strategies using this type of mechanistic knowledge. These, and many other examples, indicate that active matter is getting smarter.

References

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