Impact of Material Turnover on Diffusion in Bacterial Cell Walls: A Random Walk on a Dynamic Percolation Network

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Bacteria are typically enclosed by a cell wall, a crosslinked protective structure primarily composed of peptidoglycan. In Gram-positive bacteria, unlike species such as E. coli, the cell envelope consists of a single inner membrane surrounded by a thick peptidoglycan layer, without any known dedicated transport channels. As a result, it remains an open question how the cell wall still permits the passage of essential molecules such as nutrients and ions. The bacterial cell wall is a dynamic structure which must continuously be remodeled for growth through the insertion of new material and the cleavage of existing bonds, enabling expansion. How material turnover impacts cell wall permeability remains relatively unexplored, but it is thought to play a major role in controlling permeability.

In this work, we investigate how environmental turnover influences diffusive transport using a combination of analytical theory and simulations. Despite its broad relevance, diffusion in time-dependent disordered environments remains relatively unexplored. We show experiments can be described by a random walk on a dynamic percolation model with a diffusion coefficient that is non monotonic as a function of the turnover rate, i.e., there is a value of turnover at which the diffusion is maximized.

Furthermore, from a classical physics point of view, random walks on percolation structures are typically treated in the thermodynamic limit, where the domain is effectively infinite and finite-size effects can be neglected. In contrast, the cell wall has a finite thickness, necessitating a different approach to analyze the problem. Additionally, standard treatments assume a point-like walker occupying a single lattice site, whereas the impact of larger particle size—allowing the walker to span multiple sites—remains largely unexplored. Here, we investigate how dimensionality, particle size, and external bias influence transport in this setting.

Our results are relevant to a wide range of systems involving diffusion in evolving structures, including porous materials, polymer gels, and temporal networks in which connection nodes appear and disappear in time.

Reference:

[1] Akbary, Z., Samantaray, K., Shafir, D., Jain, K., Hocky, G. M., van Teeffelen, S., Rojas, E. R. (2025). Peptidoglycan turnover promotes active transport of protein through the bacterial cell wall. bioRxiv, 2025-09.