Stochastic geometry of fiber intersections: effects of directional bias and dimensionality reduction

Efi-maria Papia[1,2], Alex Kondi[1,3], **Vassilios Constantoudis**[1,3]

[1]Institute Of Nanoscience And Nanotechnology, Greece, [2]Department of Physics, University of Athens, Greece, [3]Nanometrisis p.c.

In the study of soft matter and physical networks, ranging from biological tissues and biopolymer gels to non-woven synthetic fabrics, macroscopic bulk material properties are fundamentally dictated by their microscopic architecture [1]. Features such as mechanical elasticity, non-linear stress response, and fluid transport capabilities are heavily influenced by the spatial distribution, connectivity, and density of fiber intersections, which act as critical force-bearing nodes and topological cross-links [2]. To elucidate how statistical orientation rules govern these emergent intersection patterns, we investigate 3d fiber networks simulated as straight lines confined in a cubic field of view.

Specifically, we model the fiber networks using isotropic Poisson line processes as well as anisotropic von Mises-Fisher distributions confined to a bounded 3D cubic domain. After extracting the spatial point patterns of pairwise filament intersections, we characterize network non-uniformity using the Nearest Neighbor Index (NNI) [3,4], a classical measure of clustering relative to complete spatial randomness.

To bridge theoretical spatial statistics with experimental microscopy, we perform three complementary structural analyses: (i) global 3D point pattern statistics, (ii) depth-limited 2D cross-sections that emulate scanning electron microscopy (SEM) imaging, and (iii) full-depth 2D planar projections. Our global 3D analysis reveals that fiber intersections inherently cluster in space. Furthermore, we find that the von Mises–Fisher concentration parameter exerts control over this clustering behavior. Our projection analyses demonstrate that mapping 3D network structures to 2D planes introduces “pseudo-clustering” artifacts, highlighting the geometric consequences of finite focal depths in real images obtained from microscopy.

This study establishes a quantitative link between fiber alignment and intersection statistics, providing a physical modeling framework for interpreting the spatial architecture of complex fibrous materials.

References:

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