




Graphizy: Memory-Enhanced Graph Construction for Computational Geometry and Temporal Network Analysis

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Software

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Summary

Graphizy is a Python package that enables researchers to construct and analyze dynamic networks from spatial coordinate data with built-in support for temporal memory tracking. The package addresses the challenge of studying evolving spatial relationships by providing a unified interface for creating geometric graphs (Delaunay triangulation, proximity graphs, k-nearest neighbors, minimum spanning trees, Gabriel graphs) while maintaining a memory of historical connections across time steps. Unlike traditional graph libraries that treat each time point independently, Graphizy's temporal memory system allows researchers to track connection persistence, analyze network stability, and visualize the evolution of spatial relationships over time. The package is optimized for real-time applications and integrates seamlessly with existing scientific Python tools including igraph and NetworkX.

Statement of Need

Analysis of spatial networks plays a crucial role across diverse scientific disciplines, from tracking animal social interactions (Krause & Ruxton, 2002) to studying particle dynamics in physics and analyzing urban mobility patterns. However, existing graph analysis tools fall short in three critical areas that limit their effectiveness for spatial-temporal research.

First, widely-used libraries like NetworkX (Hagberg et al., 2008) and igraph (Csardi & Nepusz, 2006) treat spatial coordinates merely as node attributes rather than fundamental properties that determine graph structure. Researchers must manually implement geometric algorithms to construct spatially-meaningful networks, leading to fragmented workflows and potential inconsistencies across studies.

Second, these libraries lack native support for temporal dynamics. When analyzing evolving systems—such as moving particles, migrating animals, or changing social groups—researchers must repeatedly reconstruct graphs from scratch at each time step, discarding valuable information about connection persistence and network evolution. This approach prevents the analysis of temporal patterns that are often central to understanding dynamic systems.

Third, the computational geometry workflow typically requires integrating multiple specialized libraries (SciPy for triangulation, matplotlib for visualization, NetworkX for analysis), creating barriers for researchers and increasing the likelihood of implementation errors.

Graphizy addresses these limitations by providing a unified framework that treats spatial relationships as first-class citizens and incorporates a novel temporal memory system. The package enables researchers to track which connections persist over time, identify stable network structures, and analyze the evolution of spatial relationships—capabilities that are essential for understanding dynamic systems but difficult to achieve with existing tools.

40 The temporal memory system is particularly valuable for applications where connection stability
41 matters more than instantaneous network structure. For example, in studying animal social
42 behavior, brief separations should not be interpreted as broken social bonds, and in particle
43 physics simulations, temporary disconnections due to noise should be distinguished from genuine
44 structural changes.

45 Key Features

46 Graphizy provides a comprehensive toolkit for spatial-temporal network analysis through several
47 key innovations:

48 **Unified Spatial Graph Construction:** The package implements multiple geometric algorithms
49 (Delaunay triangulation, proximity graphs, k-nearest neighbors, minimum spanning trees,
50 Gabriel graphs) through a consistent API, eliminating the need to integrate multiple specialized
51 libraries.

52 **Temporal Memory System:** The core innovation is a configurable memory layer that tracks
53 edge persistence across time steps. This system allows researchers to distinguish between
54 stable, long-term connections and transient interactions, enabling analysis of network stability
55 and evolution patterns that are impossible with traditional snapshot-based approaches.

56 **Performance Optimization:** Built on OpenCV and optimized NumPy operations, the package
57 achieves real-time performance with sub-50ms processing times for networks with 1000+ nodes,
58 making it suitable for live analysis applications.

59 **Extensible Plugin Architecture:** A flexible plugin system allows researchers to implement
60 custom graph construction algorithms while benefiting from the package's memory system and
61 visualization capabilities.

62 **Seamless Integration:** The package works alongside existing tools rather than replacing them,
63 providing easy conversion to NetworkX and igraph formats for advanced analysis while offering
64 specialized capabilities for spatial-temporal research.

65 Research Applications

66 The package provides detailed documentation for characterizing topological interactions within
67 Paramecium populations in real-time, showcasing how the temporal memory system can track
68 collective behavior patterns and spatial organization in microbial communities. This allows us
69 to study (and perturb in real time at 20 FPS) swarms topological dynamics.

70 Graphizy includes comprehensive tutorials and examples demonstrating its application to
71 real biological systems. These tutorials demonstrate the package's capability to handle high-
72 frequency spatial data and extract meaningful interaction patterns from complex biological
73 systems.

74 The package has been designed to support research across multiple domains where spatial
75 relationships and their temporal evolution are critical, including behavioral ecology (animal
76 social networks), physics and materials science (particle interaction networks), and urban
77 planning (mobility pattern analysis). The comprehensive example suite and plugin architecture
78 make it accessible for researchers across these diverse fields.

79 Performance and Validation

80 Comprehensive benchmarking demonstrates significant performance advantages over general-
81 purpose graph libraries for spatial applications. When compared to NetworkX+SciPy imple-
82 mentations, Graphizy achieves variable performance gains depending on the algorithm: 22×

83 speedup for Delaunay triangulation and analysis, $25\times$ speedup for proximity graphs, $14\times$
84 speedup for minimum spanning tree construction, and $15\times$ speedup for k-nearest neighbor
85 graphs on 1000-node networks. Overall, the package provides an average $18\times$ performance
86 improvement across all node number, graph type and tested algorithms.

87 The temporal memory system adds minimal computational overhead (few ms per update),
88 tracking connection persistence efficiently while maintaining real-time capability. Performance
89 scales well across different graph types, with speedups depending on the specific algorithm and
90 topology analysis type.

91 The package includes extensive validation through unit tests ($>50\%$ code coverage), integration
92 tests across multiple graph types, and performance benchmarks that demonstrate consistent
93 scalability. All algorithms have been validated against established implementations to ensure
94 correctness and produce structurally similar results.

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