

Biopolymer Networks: Image Analysis, Reconstruction and Modeling

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Motivation

Sources of Strain-Stiffening

- [Storm et al., 2005]: strain stiffening arises from non linearity of single chains. Under the assumption that the network is isotropic and homogeneous.
- [Onck et al., 2005], at the same time an alternative explanation of strain stiffening arises exclusively from network connectivity and relative orientation of the fibers.

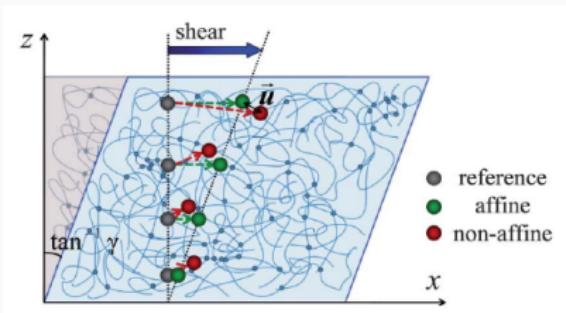
Strain-Stiffening: Validity of Affine Deformation approximation in semi-flexible polymers

Affine transformations valid when
any of this:

- Isotropic and Homogeneous Network
- Stiff Chains
- Dense Networks

Non-Affine range when:

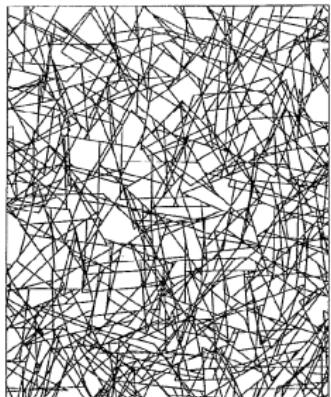
- Anisotropic Network
- Compliant Chains
- Coarse Networks



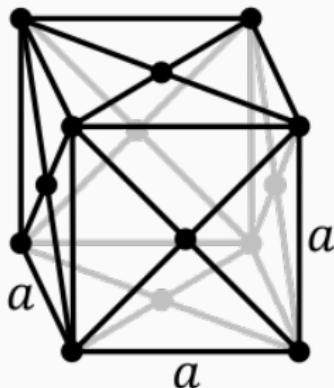
Displacement of network points under affine and non-affine regimes. [Basu et al., 2011; Wen et al., 2012]

[Wilhelm and Frey, 2003]

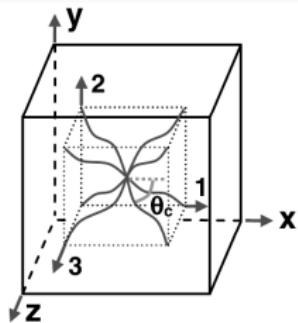
Mechanical simulations use toy network architectures



(a) Mikado model



(b) Face-centered-cube
(FCC) lattice



(c) Eight-chain model

Figure 1: Different toy models used for mechanical simulations.

Toy models? We can use real architectures gathered from 3D microscopy data

Goal of the thesis

Goals

- Extract the geometry of biopolymers networks from 3D images.

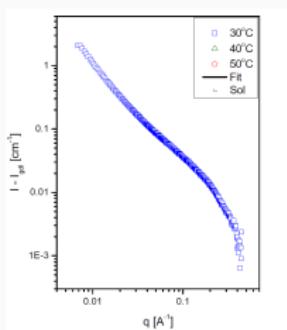
Goals

- Extract the geometry of biopolymers networks from 3D images.
- Provide software as a tool-set, enabling others to extract and analyze networks.

Challenges: Validating Microscopy Data

Scattering: SAXS and SANS

- Study of peaks and fractality at different q values provides an **averaged** structural information (mesh size, width of single-chains)
- It does not require special sample preparation.
- Good statistics, fast, allow study of dynamics.
- **But**, it does not provide explicit 3D structure of exact connectivity.



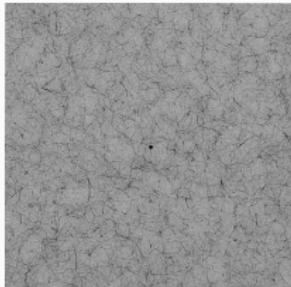
$I - I_0$ vs q Pectin from SAXS

Microscopy: TEM and Confocal

To get detailed connectivity we need **3D microscopy**.

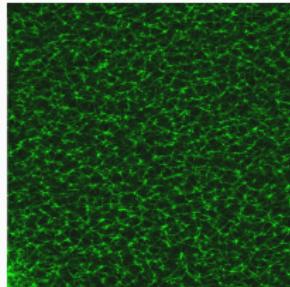
TEM tomography

- Necessary to reach polysaccharides scale.
- Sample preparation is hard.
Artifacts?
- In chapter 2 we concluded that network size features can be trusted.



Confocal

- Suitable for most protein biopolymer networks.
- Sample preparation is more reliable.



Challenges: Image Denoising and Skeletonization

Image Denoising and Skeletonization

Wavelet denoising

Developed Isotropic Wavelets framework to remove noise, and aid with the segmentation in the extraction pipeline.

Skeletonization algorithms

1. Developed state of art method from Digital Topology fields to get a thin skeleton representation of the biopolymer network.

Extraction of Architecture and Graph Characterization

From Images to Spatial Graphs

Goal:

Process raw image data to get a spatial graph representation of the network.

Steps:

1. **Pre-processing:** Enhance signal to noise ratio with pre-processing (denoise).
2. **Segmentation:** Extract object of interest from image. Binary image.
3. **Skeletonization:** Thin representation of the object.

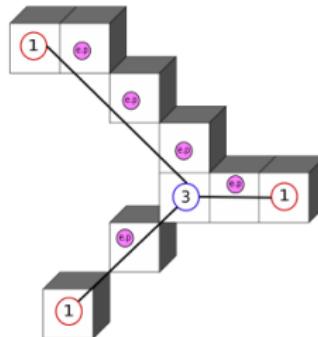
The skeleton will then be adapted into a **Graph** for characterization.

Graphs: A Link to Complex Systems

A graph is a representation of connected components in terms of nodes and edges/links.

Spatial Network of biopolymers:

- A node corresponds to a junction/crosslink of biopolymers.
- An edge represents the polymer-chain itself.



Graphs are a powerful tool connecting to the field of **Complex Systems**.

We want to take advantage of all those existing algorithms for **characterization** of soft materials.

Characterization of graphs: Statistical Distributions

We are able to analyze the graph to gather statistical distributions of some properties:

Degree: Geometrical distribution

$$N(p) = q(1-q)^{p-3}$$

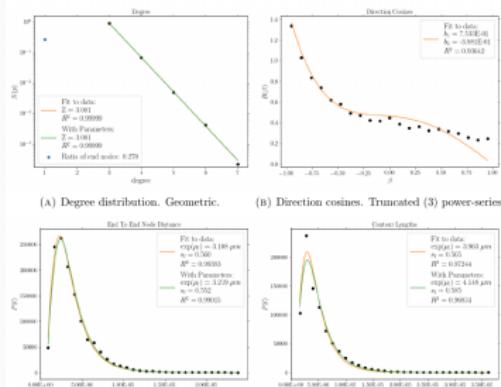
where $q = 1/(Z - 2)$, and Z is the average node degree.

Node-to-node dist.: Log-normal

$$P(\ell) = \frac{1}{\ell s \sqrt{2\pi}} \exp\left(-\frac{(\mu - \ln \ell)^2}{2s^2}\right)$$

Edge relative orientation: Power-Series

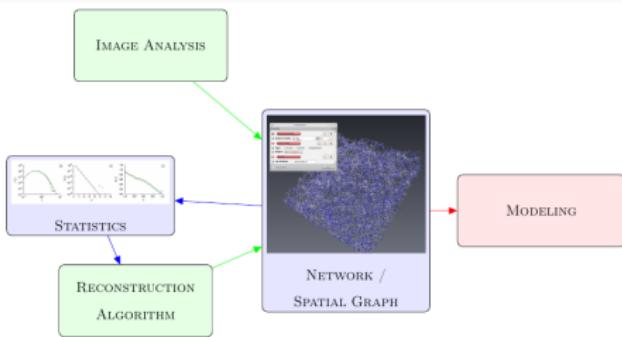
$$B(\beta) = \sum_{k=1}^m b_k (1 - \beta)^{2k-1}$$



Protein and polysaccharides networks share the same **functional distributions** for degree, end-to-end distances, contour-lengths and angles.

Reconstruction algorithm

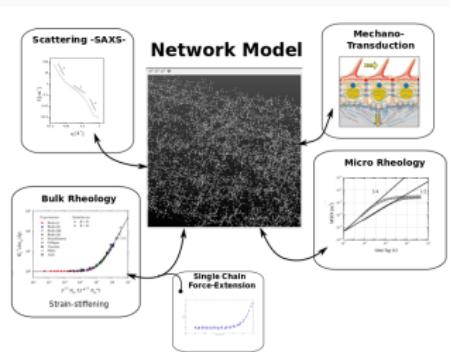
- Also provided, as a exploratory tool for different networks architectures is the reconstruction algorithm.
- From the set of statistical distributions, it is able to generate the full geometry of a network which follows the targeted distributions.



Conclusions

Exploring network geometries:

- Provide software for reliably extract biopolymer networks from 3D images
- Link to complex network libraries for graph analysis. **Reconstruct in-silico networks from it**
- The tool-set developed provide soft-matter scientists to use these networks for simulations and characterization of materials.



Thanks!

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- The power law behaviour has derived from universal slope of 1 ? to **surprisingly(?)** a slope of 3/2. We think that this data require a further explanation beyond the assumption that collagen is somehow an exception in that universality claimed years ago.
- The shift to strain stiffening, or the beginning of a nematic phase of partially oriented fibers, might depend on architecture.

Acknowledgments



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*for Advanced Materials
and Nanotechnology*



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- Leif Lundin. SP Food and Bioscience. Sweden.



Dr. Brad Mansel, New Zealand

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Segmentation I

Goal: Extract feature or region of interest from the raw image.

Noise is the enemy. But also crowded environments from where only a specific feature is needed.

Main Segmentation Methods:

- **Threshold-Based:** Threshold at an intensity value. Entropy minimizing (Otsu) or other criteria.
- **Enhancement Filter:** Local-phase studies or eigenvalue analysis of Hessian matrix.
- **Deformable-Model:** Curve evolving under vector field to fit structure. LevelSet (closed curve) or Snakes (open).

Segmentation in Confocal and TEM images of biopolymers

Need of preprocessing steps to reduce noise and enhance features of interest.

Pre-processing pipeline:

- Multiscale characterization convolving image with gaussian operator of different sigmas/scales
- Denoise: Anisotropic edge-preserving filter.
- Enhancement Filter: Use a local-phase filter using a **monogenic-signal**, a N-D extension to the **analytic signal** used in modulation and demodulation of 1D communication signals.



Insight Toolkit: Registration and Segmentation

I am implementing a monogenic signal filter to ITK, the insight toolkit for image segmentation based on [Chenouard and Unser, 2011].

This filter applies operators in each direction of the FFT space, enhancing edge and line structures. It uses local phase information, and not absolute intensity, which helps detecting weak features.

It is almost finished. I have to do the eigenanalysis to the filter and contribute (again) to this open source library.

ITK is the main library for image analysis in C++, specially useful in segmentation of medical images and 3D stacks.

Segmentation after the enhancement of the monogenic filter

After enhancement with the monogenic filter two options:

- The monogenic signal phase can be used to detect lines and edges. Use this measure to detect edges (more reliable than gradient or Sobel). Then use a level-set method, where the edge-measure is used to set the external vector field constraining the evolution [Rajpoot et al., 2009].
- Exploit monogenic filter steering (rotation) properties. This allows to set an Eigensystem to find at each pixel the direction that maximizes the signal. Then threshold the enhanced image to get the segmentation [Chenouard and Unser, 2011].

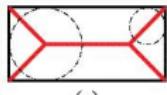
Skeletonization of segmented image

After segmentation, we have to thin the resulting binary object to a one-pixel wide representation that conserves topology.

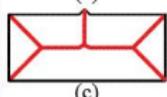
Skeletonization is really sensitive to noise in the borders, so a pruning is always required.

Global pruning:

- It applies after the skeleton has been extracted.
- Only takes into account length of branches removing short but thin branches that might be significant for the architecture.



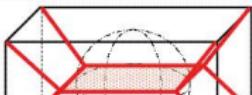
(a)



(c)

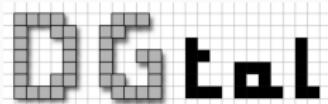
Local pruning:

- Novel method to pruning at the same time than skeleton is generated.
- The pruning is made locally, thanks to a measure of **length of branch versus thickness**.
- It conserves short branches that are locally thin, but deletes short branches that are thick (see figure)



(b)

Skeletonization: Cubical Complexes



DGTal:: Digital topology library

I have already contributed to DGtal the implementation of this local prune algorithm based on [Couprie and Bertrand, 2015].

And I am in the developing team!

VoxelComplex: CriticalKernels framework #1147

[Open](#) phcordan wants to merge 1 commit into 306d1-remaster from jscien:voxelcomplex-with-object-graph

Conversation 0 Commits 0 Files changed 37 +5,107 -321

phcordan commented on Mar 16

PR Description

Implementation of Critical Kernel framework based on M.Couprie and G.Bertrand articles:

- Asymmetric parallel 3D thinning scheme and algorithms based on isthmuses.
- Powerful Parallel and Symmetric 3D Thinning Schemes Based on Critical Kernels
- A 3D Sequential Thinning Scheme Based on Critical Kernels

Add general description of framework for docs.

Add LookUpTable Interface from #1155 (speeds an order of magnitude)

CLI script for testing in any image (future PR in DGtalTools)

Labels None yet

Milestone No milestone

Assignee No one assigned

Notifications [Unsubscribe](#)

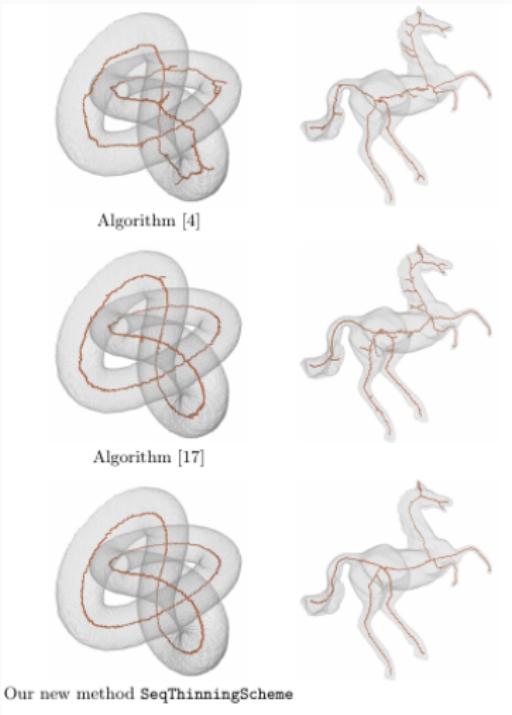
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2 participants

Skeletonization: Cubical Complexes

Global pruning:

- Uses a framework called CubicalComplexes or VoxelComplexes, where a spel (voxel in 3D, pixel in 2D) is composed by points, lines and faces.
- This allow to define a topology property called Isthmus in all those components, that preserves topology in the skeletonization process.



Pipeline:

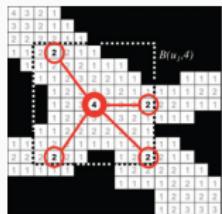
Multiscale analysis and denoise: Detect vessels of different radius.

Summary of image analysis

Pipeline:

Multiscale analysis and denoise: Detect vessels of different radius.

Segmentation: Get a binary object that conserves features.



Summary of image analysis

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Skeletonization: One-pixel wide (thin) representation of binary object, conserving topology.



Summary of image analysis

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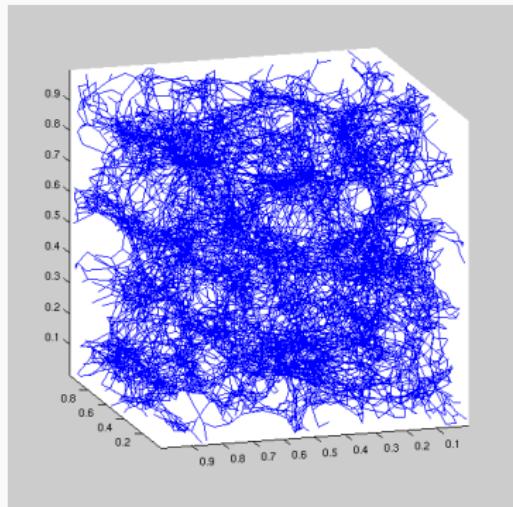
Multiscale analysis and denoise: Detect vessels of different radius.

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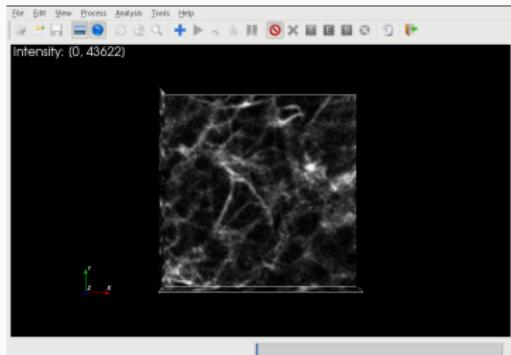
Skeletonization: One-pixel wide (thin) representation of binary object, conserving topology.

Graph adaptor: Transform skeleton to a graph, to connect with ComplexSystems tools for characterization.





Reconstruct in-silico network from
graph statistical distributions



Not revealed yet (sorry!): Merge of

software when segmentation is ready.
SGEXT: Spatial Graph Extractor.
Name suggestions welcome!
(MAIDEN?)