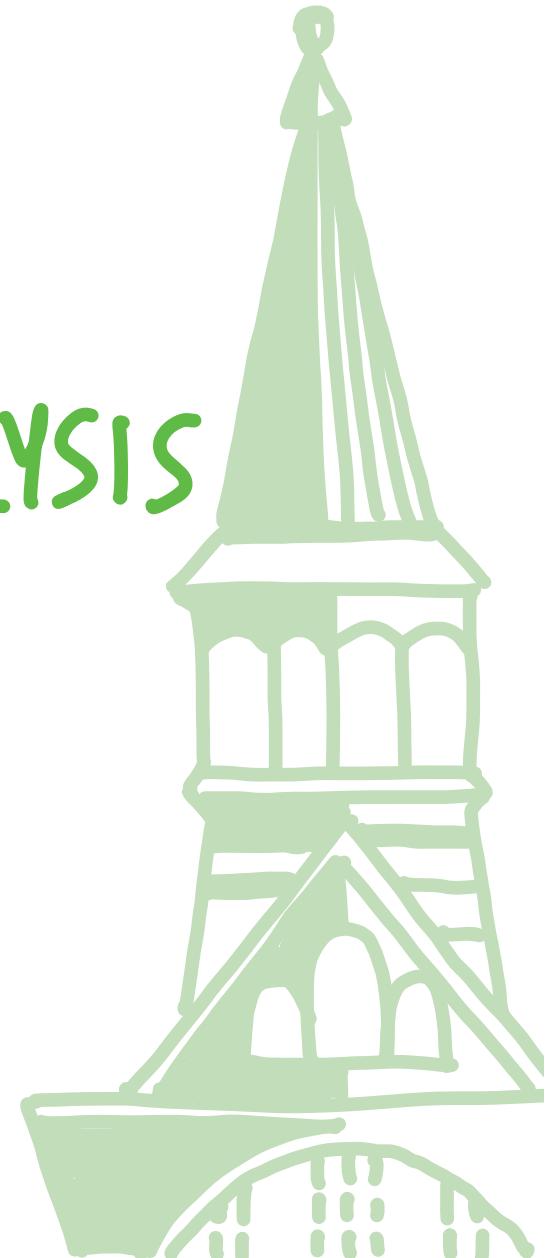


Introduction to TOPOLOGICAL DATA ANALYSIS

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VERMONT COMPLEX SYSTEMS CENTER

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The theory

data

complexes

filtrations

structure

persistence modules

homology and barcodes

function

sheaves

sheaf cohomology

The application

brain data

Alzheimer disease

brain dynamics



What is data?

Let M be a topological space

M is unknown, we want to study it, but we can only collect discrete random samples

What is data?

Let X be a topological space

D is unknown, we want to study it, but we can only collect discrete random samples

data set $\overrightarrow{D} \subseteq X$

What can we learn about X from D ?
and how can do we do it without bias?

What do I mean about Bias?

When the theoretical model is unknown, coordinates are not necessarily meaningful

Similarly, metrics in data sets are not always justified

choosing a parameter gives a partial view

Topology is the cure to all evil !

(IRONY)

When the theoretical model is unknown, coordinates are not necessarily meaningful
coordinate-free method

Similarly, metrics in data sets are not always justified
ignore the quantitative values of distance function
and get information only the nearness of points

choosing a parameter gives a partial view

Construct summaries of information over whole domains of parameters

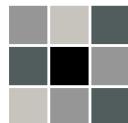
On the local behaviour of spaces of natural images

G. Carlsson, T. Ishkhanov, V. de Silva, A. Zomorodian (2008)

Data : 3x3 patches from images

They can be seen as points in 9-dimensional space

normalized to have average = "gray"
 $\text{norm} = 1$ } \Rightarrow the points lay on a 7-sphere



On the local behaviour of spaces of natural images

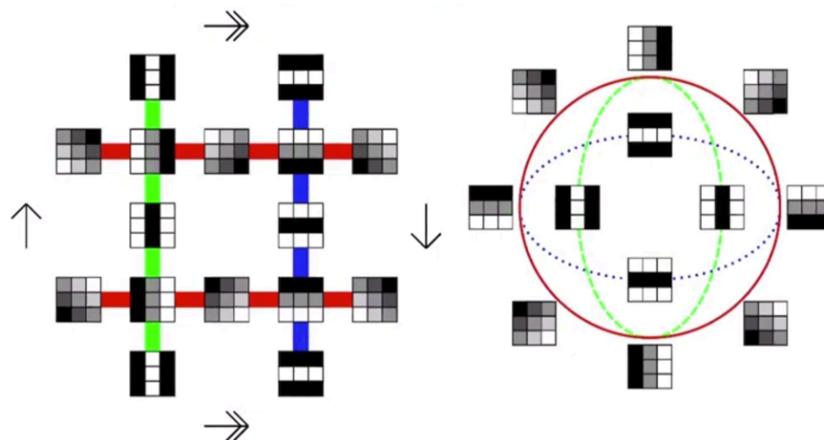
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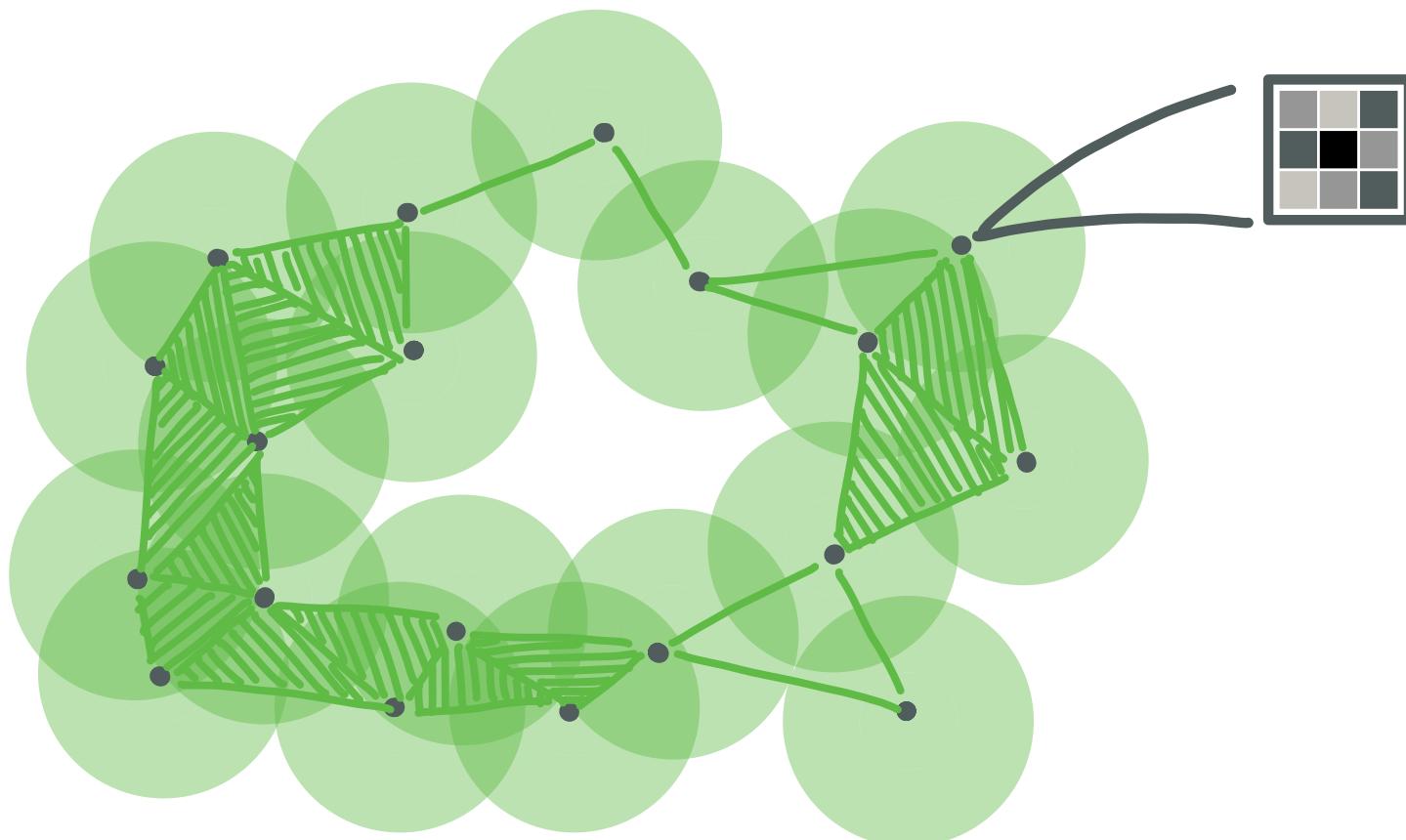
normalized to have average = "gray"
norm = 1 } \Rightarrow the points lay on a 7-sphere

using topological data analysis they were able to
find out that the subspace the data comes from has
the same homology type as the **KLEIN BOTTLE**



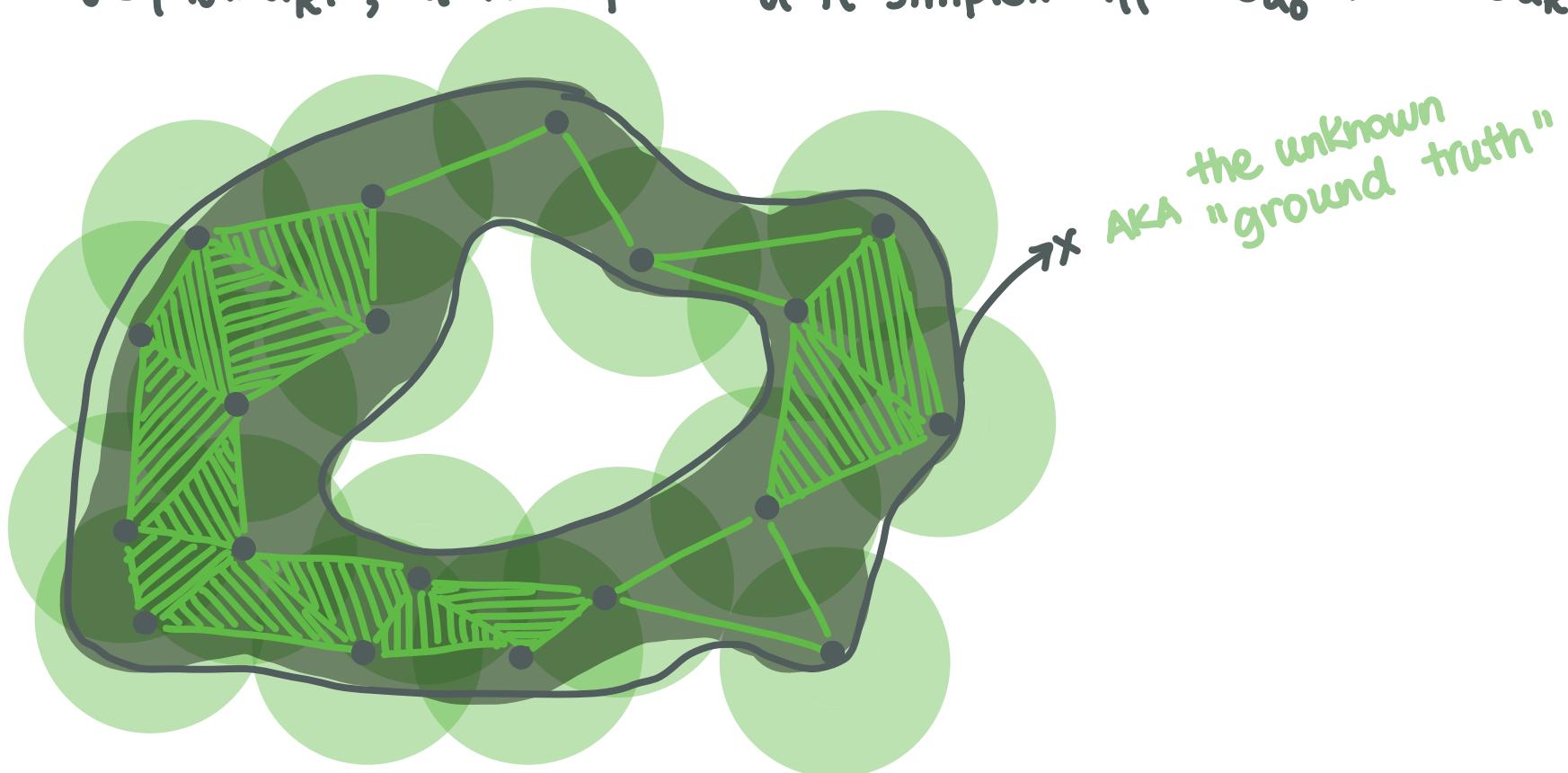
How to go from data to a structure ?

In this case the data set comes with an intrinsic metric
then we can construct a simplicial complex from it.



Nerve

let X be a topological space and $\mathcal{U} = \{U_\alpha\}_{\alpha \in A}$ a covering of X .
The **nerve** of \mathcal{U} is an abstract simplicial complex with vertex set A .
 $\sigma = \{a_0, \dots, a_K\}$, $a_i \in A$ spans a K -simplex iff $U_{a_0} \cap \dots \cap U_{a_K} \neq \emptyset$



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Theorem

Let X be a topological space, $\mathcal{U} = \{U_\alpha\}_{\alpha \in A}$ a countable open covering of X s.t. $\forall S \subseteq A$ with $S \neq \emptyset$ $\bigcap_{\alpha \in S} U_\alpha$ is either contractible or empty
Then $N(\mathcal{U})$ is homotopy equivalent to X .

Let K be a simplicial complex. A **filtration** F is a nested sequence of strictly increasing subcomplexes of K $F_1K \subsetneq F_2K \subsetneq \dots \subsetneq F_nK = K$

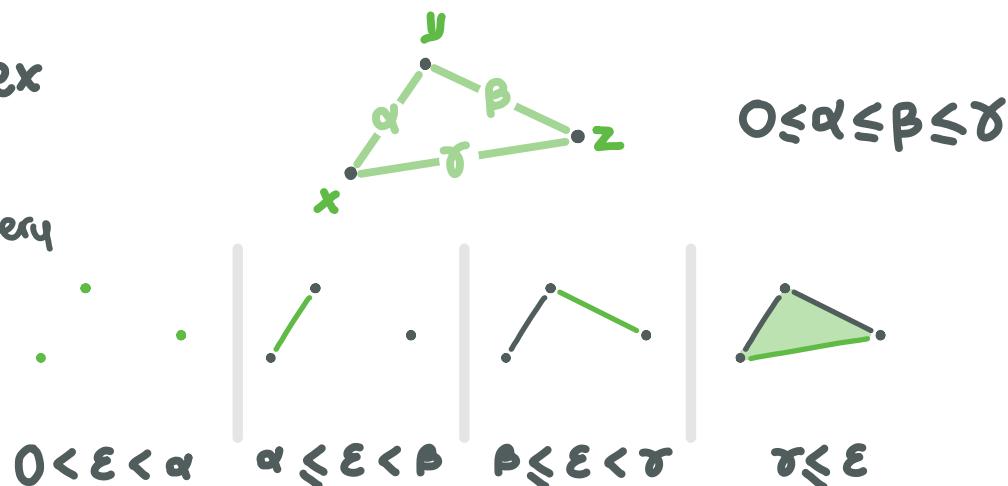


Vietoris-Rips filtration

$\text{VR}(X, \varepsilon)$ is a simplicial complex

$$\sigma = \{a_0, \dots, a_K\}, a_i \in A$$

$\sigma \in K$ iff the distance between every pair of points in σ is at most ε



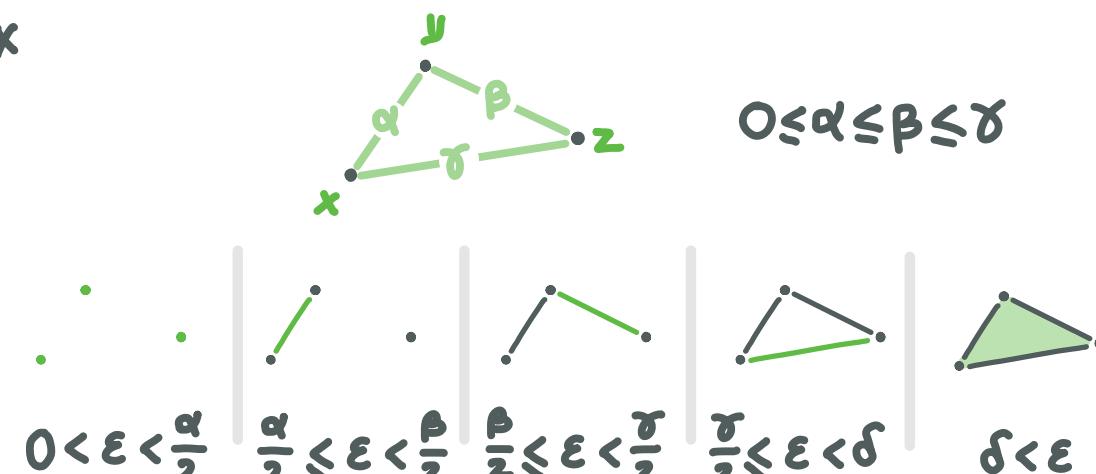
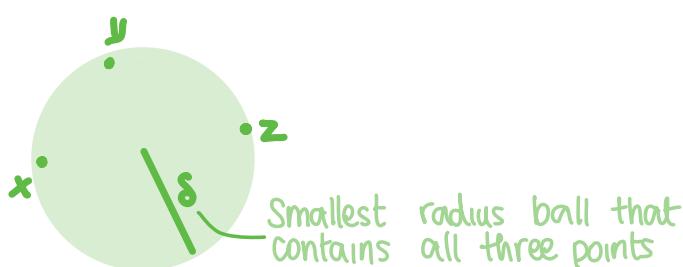
Čech filtration

$\check{C}(X, \varepsilon)$ is a simplicial complex

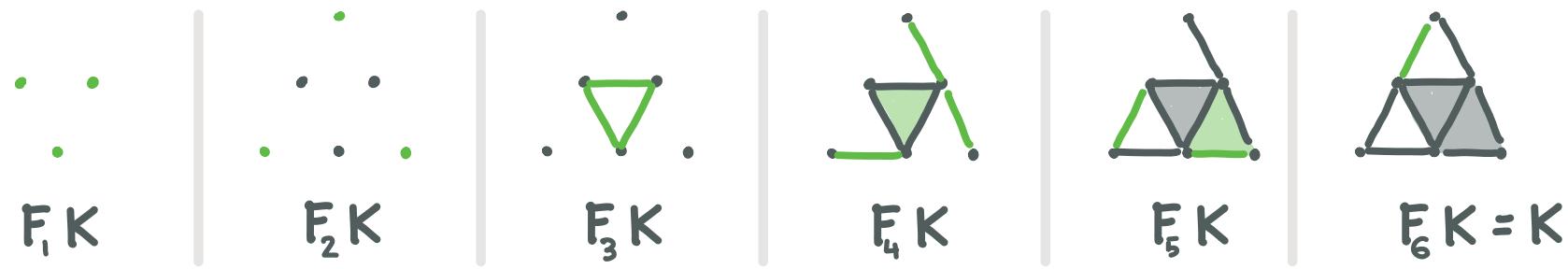
$$\sigma = \{a_0, \dots, a_K\}, a_i \in A$$

$\sigma \in K$ iff $B_{d_0}^{(\varepsilon)} \cap \dots \cap B_{d_K}^{(\varepsilon)} \neq \emptyset$

$B_x^{(\varepsilon)}$ = ball centered in x of radius ε



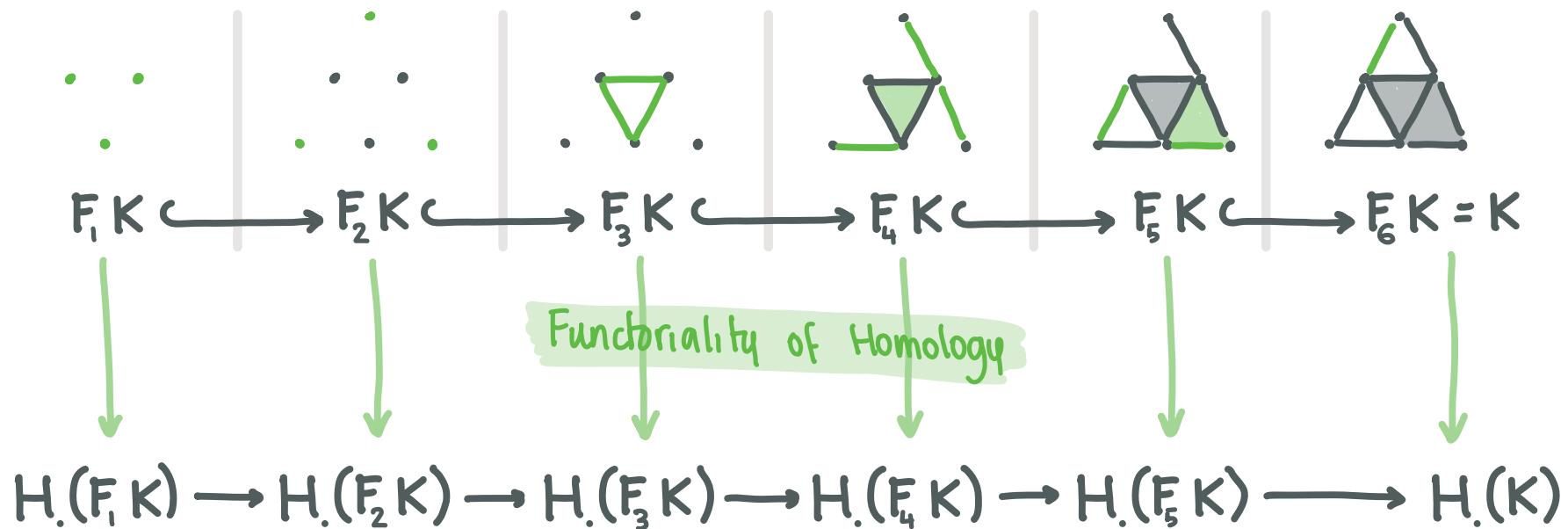
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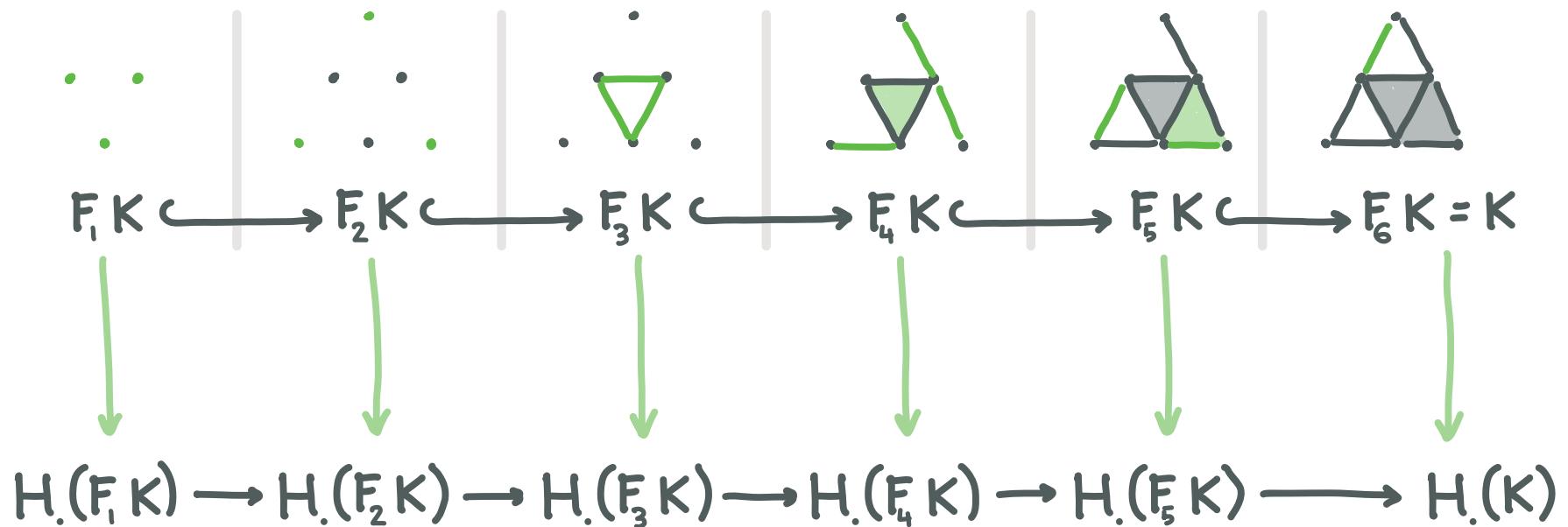
Functionality of Homology

- If $f: K \rightarrow L$ and $g: L \rightarrow M$ simplicial maps then $C.(g \circ f) = C.(g) \circ C(f)$
- If $\varphi: (C, d) \rightarrow (C', d')$ and $\psi: (C', d') \rightarrow (C'', d'')$ chain maps then
 $H_*(\psi \circ \varphi) = H_*(\psi) \circ H_*(\varphi)$

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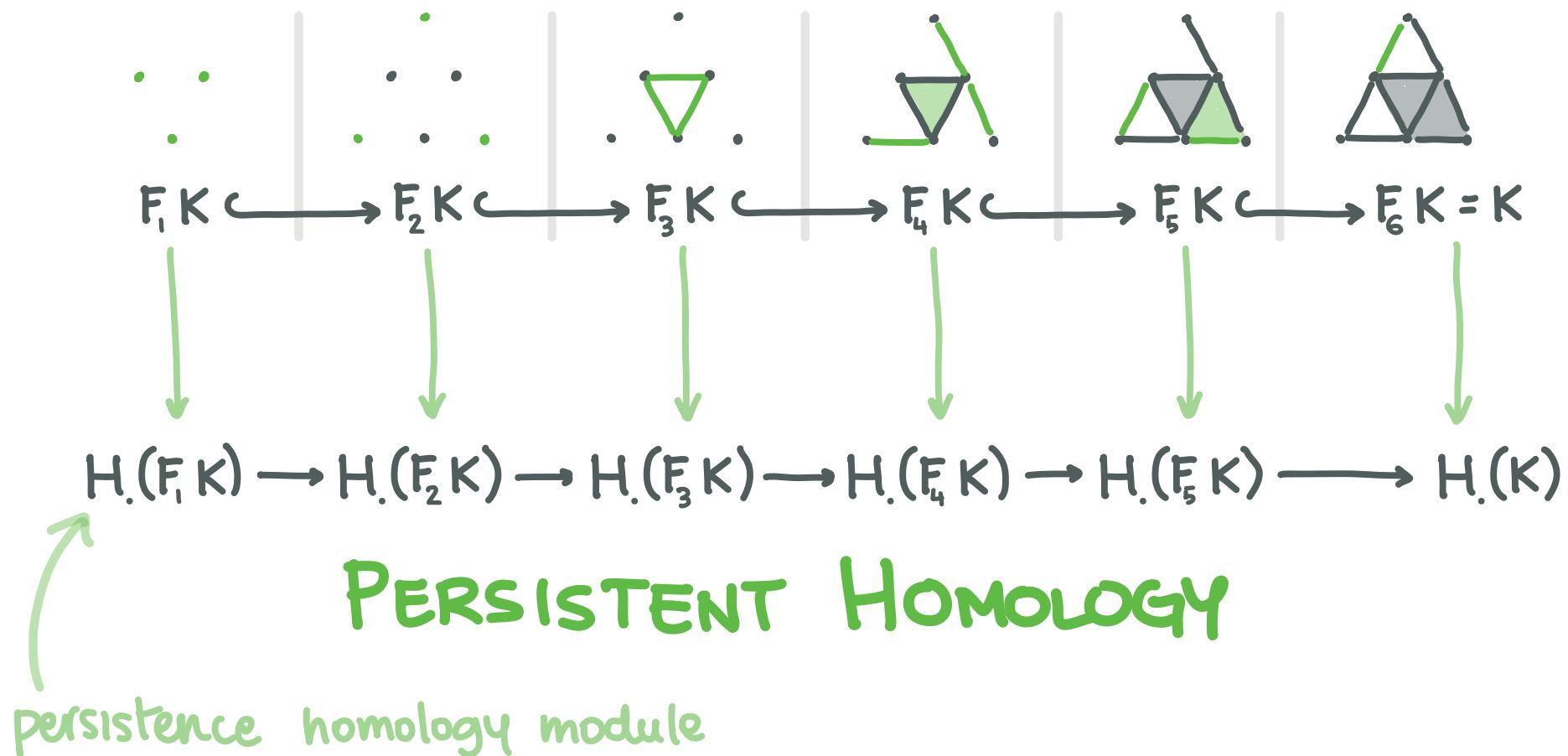


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PERSISTENT HOMOLOGY

Let K be a simplicial complex. A filtration F is a nested sequence of strictly increasing subcomplexes of K $F_1K \subsetneq F_2K \subsetneq \dots \subsetneq F_nK = K$



A (discrete) **persistence module** is a pair (V_\cdot, a_\cdot) of vector spaces $\{V_i : i \in \mathbb{N}\}$ and linear maps $a_i : V_i \rightarrow V_{i+1}$

$$V_0 \longrightarrow V_1 \longrightarrow \dots \longrightarrow V_i \longrightarrow V_{i+1} \longrightarrow \dots$$

Warning! This is not necessarily a complex (i.e. $a_i \circ a_{i+1}$ is not always =0)

A (discrete) **persistence module** is a pair (V, a) of vector spaces $\{V_i : i \in \mathbb{N}\}$ and linear maps $a_i : V_i \rightarrow V_{i+1}$

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Persistence modules form a category!

A morphism of persistence modules $\varphi : (V, a) \longrightarrow (W, b)$

$$\begin{array}{ccccccc} V_0 & \xrightarrow{a_0} & V_1 & \xrightarrow{a_1} & \dots & \longrightarrow & V_i & \xrightarrow{a_i} & V_{i+1} & \longrightarrow & \dots \\ \varphi_0 \downarrow & & \varphi_1 \downarrow & & & & \varphi_i \downarrow & & \varphi_{i+1} \downarrow & & \\ W_0 & \xrightarrow{b_0} & W_1 & \xrightarrow{b_1} & \dots & \longrightarrow & W_i & \xrightarrow{b_i} & W_{i+1} & \longrightarrow & \dots \end{array}$$

If $\forall i \quad \varphi_i$ is invertible, then φ is an **isomorphism**

The direct sum of persistence modules $(V, a) \oplus (W, b) = (V \oplus W, a \oplus b)$

$$V_0 \oplus W_0 \xrightarrow{a_0 \oplus b_0} V_1 \oplus W_1 \xrightarrow{a_1 \oplus b_1} \dots \longrightarrow V_i \oplus W_i \xrightarrow{a_i \oplus b_i} \dots$$

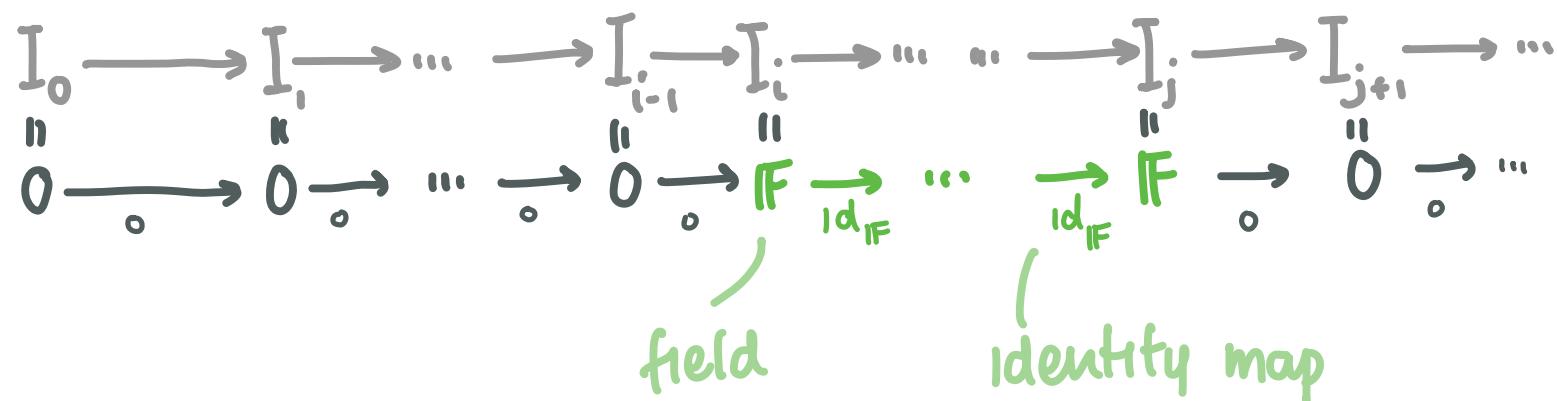
A persistence module is indecomposable if it admits no interesting direct sum decomposition

$$\text{If } (I, c) \cong (V, a) \oplus (W, b) \quad \text{then} \quad \begin{cases} (V, a) \cong (I, c) \\ (W, b) \cong (0, 0) \end{cases}$$

isomorphism

Property

Persistence modules of the following type are indecomposable
 for $i \leq j$ with $i, j \in \mathbb{N}$

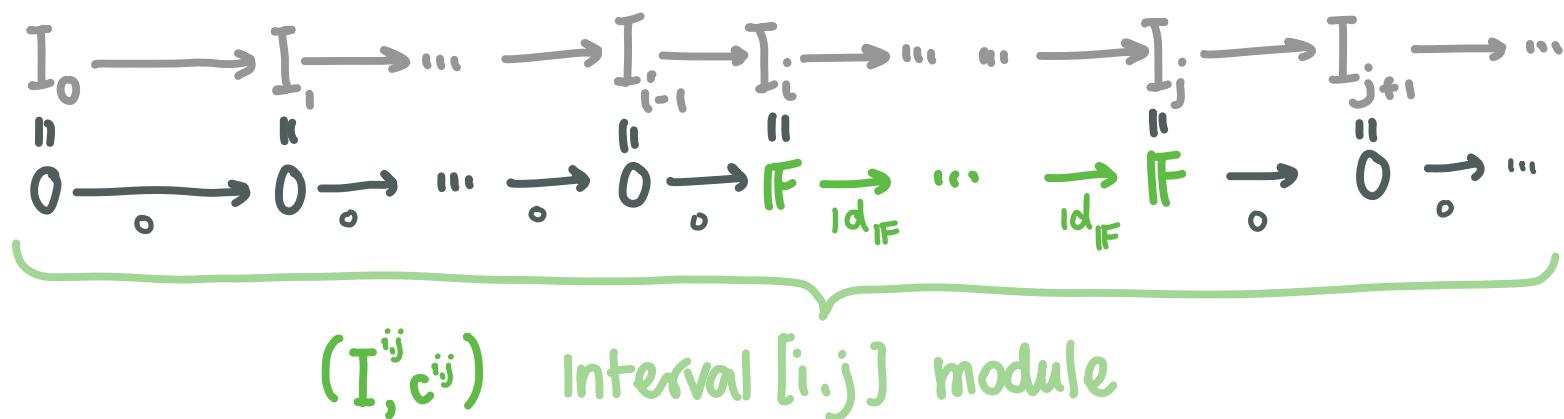


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Decomposition Theorem

$\forall i \dim V_i < \infty$ and $a_i : V_i \rightarrow V_{i+1}$
 a_i is isomorphism $\forall j > 0$

Let (V, a) be a finite type persistence module then exists a finite set of intervals $\text{Bar}(V, a) = \{[i, j] \mid i \in \mathbb{N}, j \in \mathbb{N} \cup \{\infty\}, j \geq i\}$ and a multiplicity $\mu : \text{Bar}(V, a) \longrightarrow \mathbb{N}$ so that:

$$(V, a) \simeq \bigoplus_{[i, j] \in \text{Bar}(V, a)} (I^{ij}, c^{ij})^{\mu[i, j]}$$

 Barcode decomposition

(idea)

PROOF uses the classification of freely generated $\mathbb{F}[t]$ -modules into a free and torsion part. Because there is a lemma saying that we can always represent a persistence tame module as a graded module over $\mathbb{F}[t]$

Decomposition Theorem

(or tame)

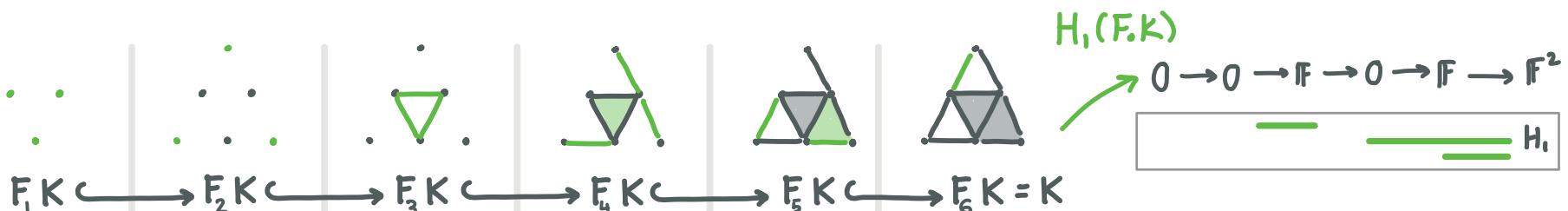
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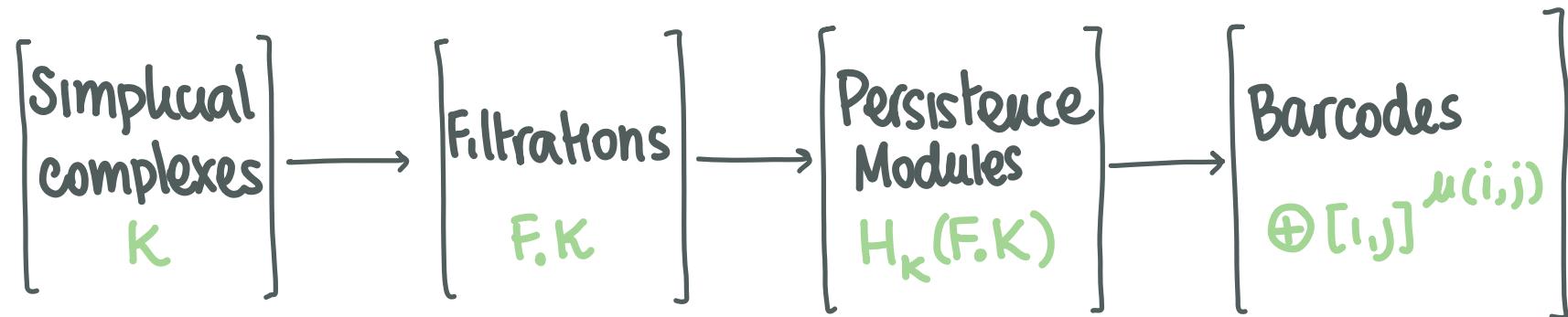
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Barcode decomposition

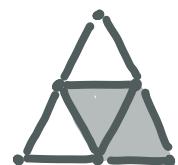
The Barcode decomposition is unique up to reordering of factors



Persistent Homology



example



$$\begin{array}{ccccccc} 0 & \xrightarrow{\quad} & 0 & \xrightarrow{\quad} & \mathbb{F} & \xrightarrow{\quad} & 0 \\ & & & & \downarrow & & \\ & & & & \mathbb{F} & \xrightarrow{\quad} & \mathbb{F}^2 \end{array}$$



$$F_1 K \hookleftarrow F_2 K \hookleftarrow F_3 K \hookleftarrow F_4 K \hookleftarrow F_5 K = K \quad H_1(F_1 K) \rightarrow H_1(F_2 K) \rightarrow H_1(F_3 K) \rightarrow H_1(F_4 K) \rightarrow H_1(K)$$

The theory

data

complexes

filtrations

structure

persistence modules

homology and barcodes

function

sheaves

sheaf cohomology

← YOU ARE HERE!

The application

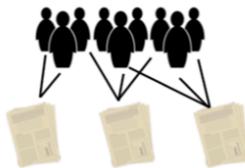
brain data

Alzheimer disease

brain dynamics



Applications



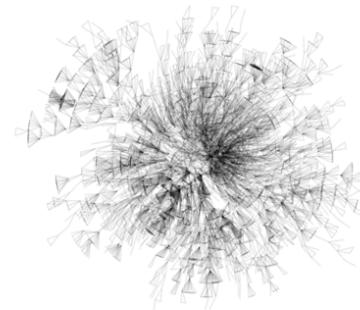
collaboration networks



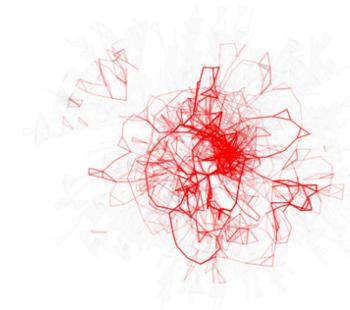
The shape of collaboration

A Patania, F Vaccarino, G Petri - EPJ Data Science (2017)

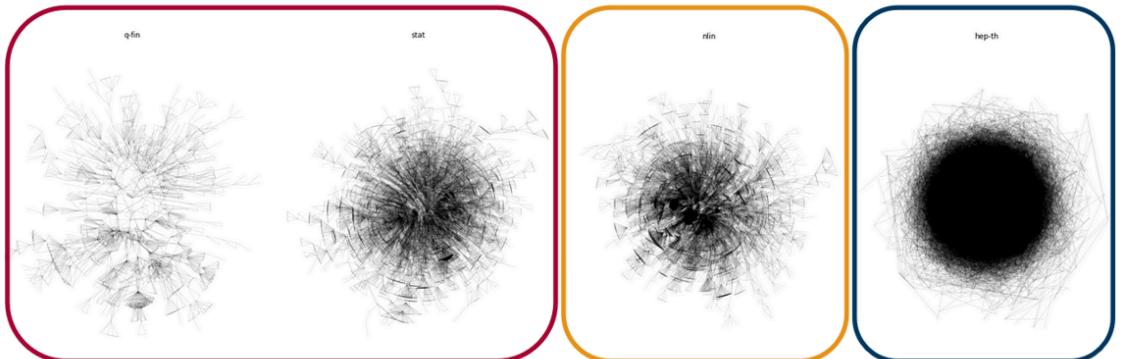
math-ph



math-ph

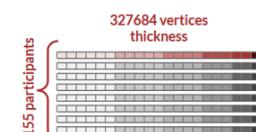
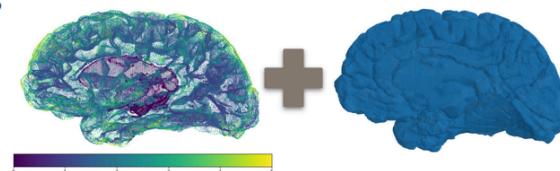


Examples for the biggest connected component for each group.

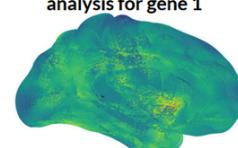


Applications

Cortical thickness



Beta coefficients of regression analysis for gene 1



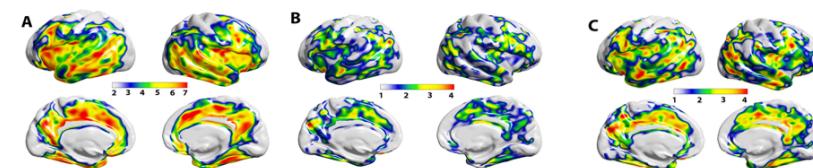
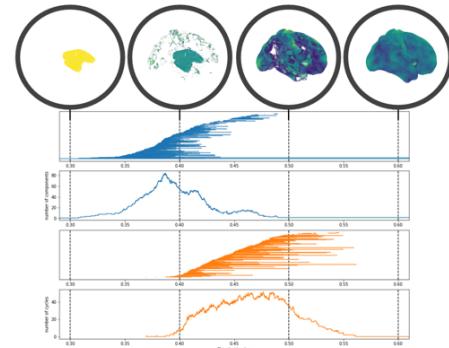
National Institutes
of Health



R21 - Integrative Predictive Modeling of Alzheimer's Disease

NIH Exploratory/Developmental Research Grant

Persistent Homology

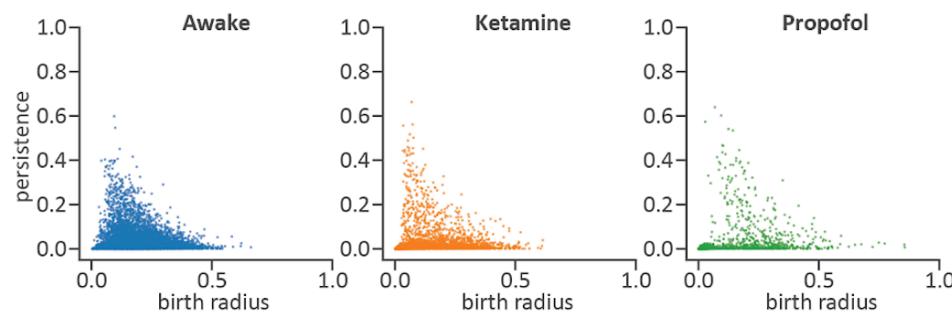
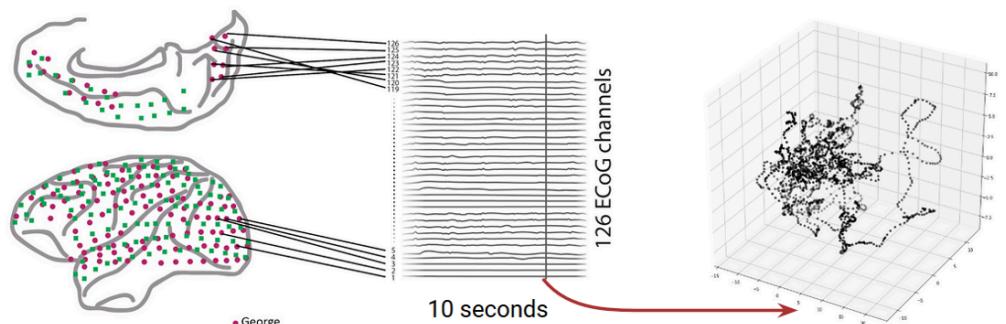
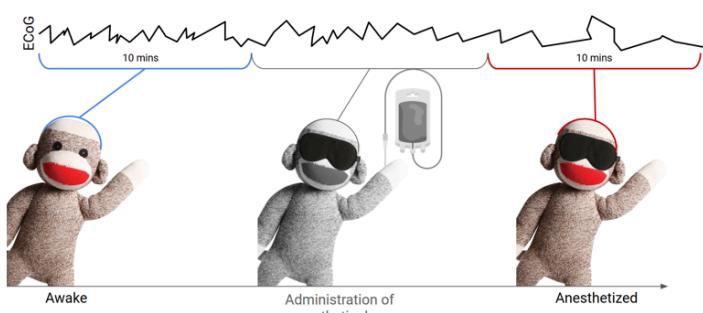


Cluster association(T-statistic) with cortical thickness($T>1.96$, $p<0.05$)
(A) Cluster 5 (B) Cluster 14 (C) Cluster 20

Characterization of genetic expression patterns in Mild Cognitive Impairment using a multiomics approach and neuroimaging endophenotypes
A Bharthur Sanjay, A Patania, X Yan, D Svaldi, T Duran, N Shah, E Chen, LG Apostolova (2021)

Applications

Neurotycho - The experiment



Topological Analysis of Differential Effects of Ketamine and Propofol Anesthesia on Brain Dynamics

T F. Varley, V Denny, O Sporns, A Patania (2021) in submission Open Science ([bioarxiv- https://doi.org/10.1101/2020.04.04.205437](https://doi.org/10.1101/2020.04.04.205437))

A simplicial map $f: K \rightarrow L$

$$\begin{array}{ccc} & f: K \longrightarrow L \\ & \sigma \longmapsto f(\sigma) \end{array}$$

where $f(\sigma)$ is a simplex of L such that $\dim f(\sigma) \leq \dim(\sigma)$ and if $\dim \sigma = 0$, $\dim f(\sigma) = 0$

Let $f: K \rightarrow L$ simplicial map, the fiber of $\tau \in L$ is the set τ_f
 $\tau_f = \{a \in K \mid f(a) \subseteq \tau\}$
 these are the simplices of K that end up being faces of the simplex τ

Proposition

- i) τ_f is a subcomplex of K
- ii) $\tau_f \subseteq \tau'_f$ inclusion of simplicial complexes

then the assignments $\tau \mapsto H_k(\tau_f)$
 $\tau \subseteq \tau' \mapsto H_k(\tau_f \hookrightarrow \tau'_f)$ constitute a sheaf over L
 because homology is a functor

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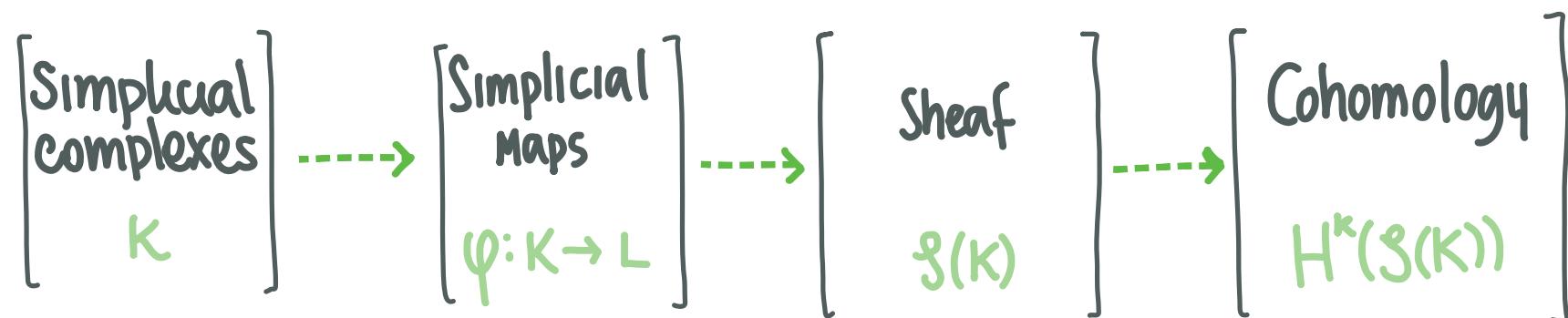
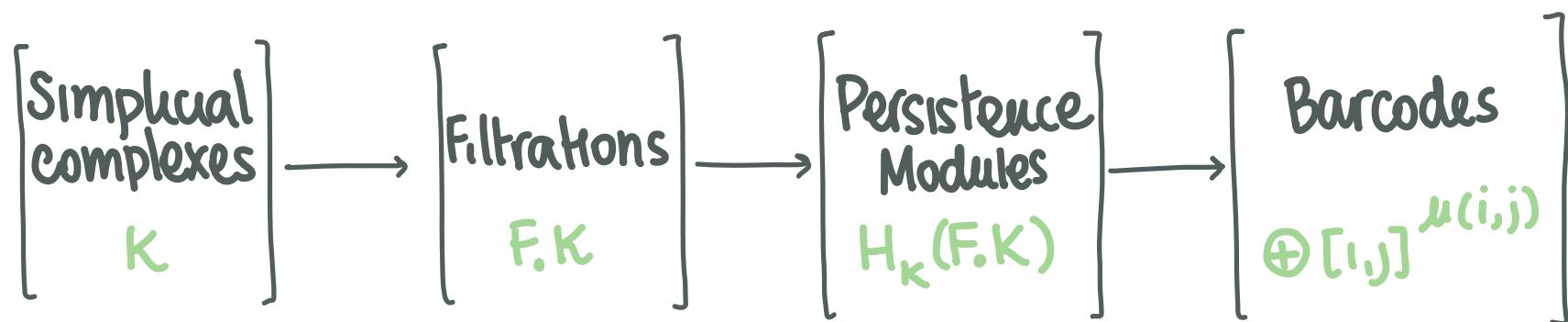
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Homology is a functor then $\forall \tau \in L$

$$\begin{aligned} \tau &\mapsto H_k(\tau_{/f}) \\ \tau \subseteq \tau' &\mapsto H_k(\tau_{/f} \hookrightarrow \tau'_{/f}) \end{aligned}$$

This is a well known construction in topology: a sheaf!

Sheaves



A sheaf on a simplicial complex is a functor

L as a poset is a category

$$\mathcal{S}: (L, \leq) \rightarrow \text{Vect}_{\mathbb{F}}$$

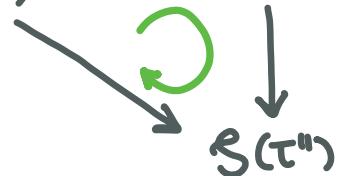
category of vector spaces over a field

\mathcal{S} assigns to each simplex $\tau \in L$ a vector space $\mathcal{S}(\tau)$ called the stalk of \mathcal{S} over τ
inclusion $\tau' \subseteq \tau$ a linear map $\mathcal{S}(\tau' \subseteq \tau): \mathcal{S}(\tau') \rightarrow \mathcal{S}(\tau)$ restriction map

such that the following hold:

identity $\tau = \tau$ is sent to identity map
associativity $\forall \tau \subseteq \tau' \subseteq \tau'' \quad \mathcal{S}(\tau) \xrightarrow{\quad} \mathcal{S}(\tau') \xrightarrow{\quad} \mathcal{S}(\tau'')$

diagram commutes



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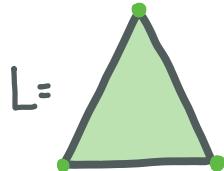
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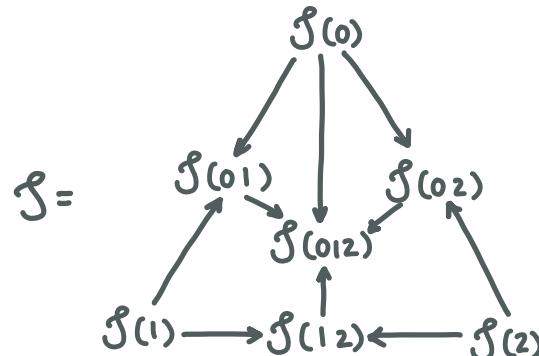
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diagram commutes

small example



Simplicial complex



A sheaf on a simplicial complex is a functor

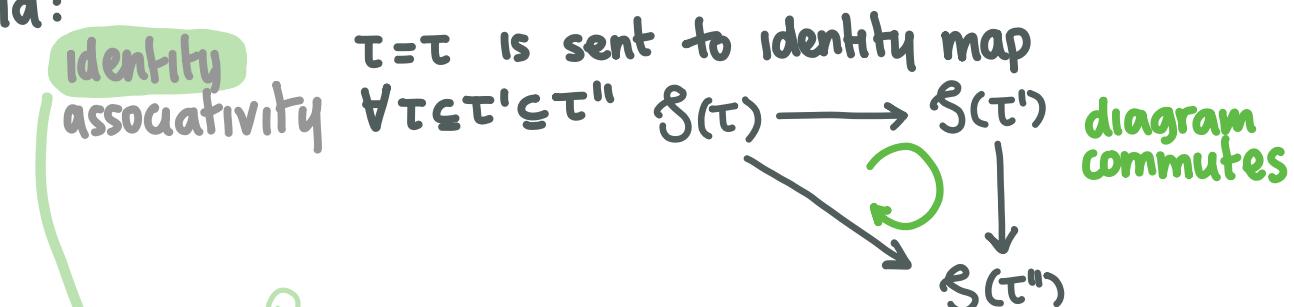
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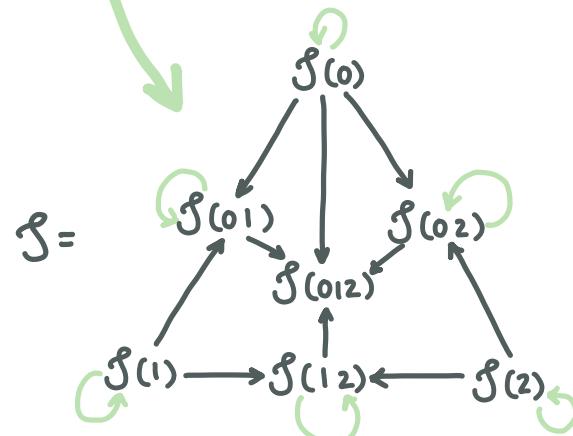
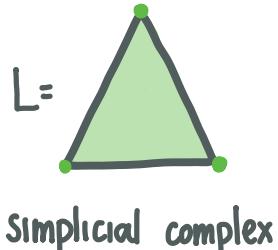
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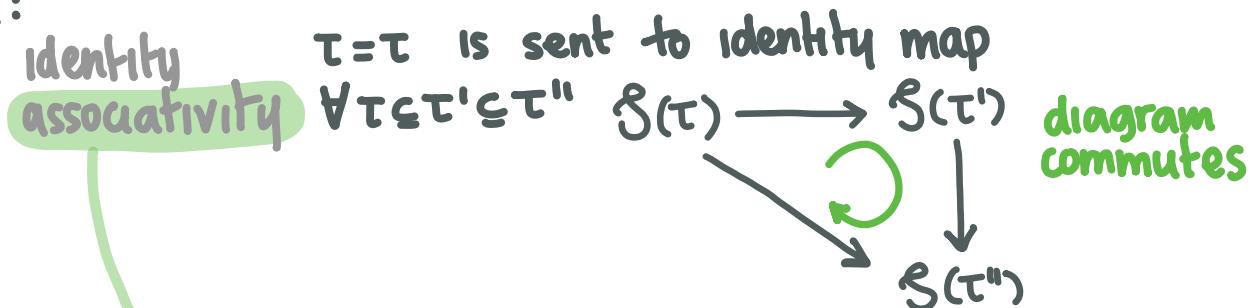
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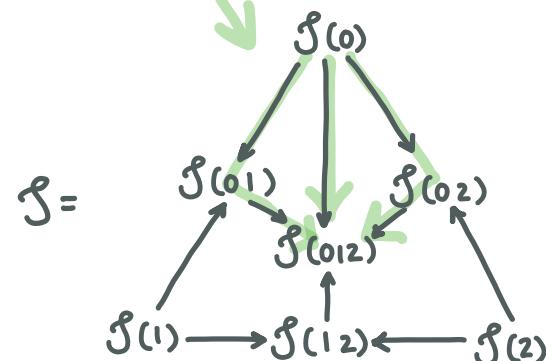
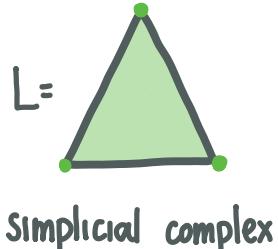
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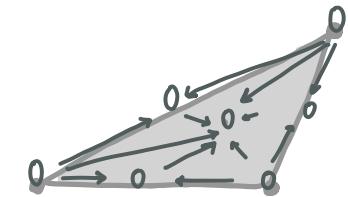
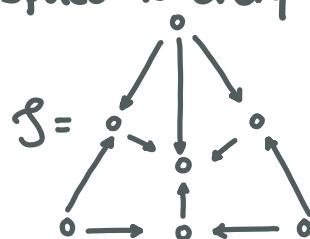
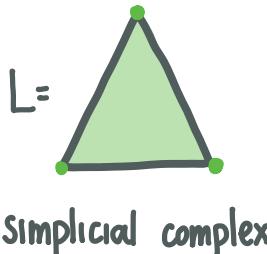


small example

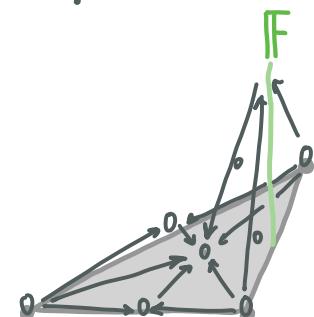
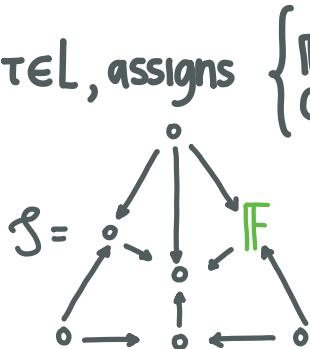
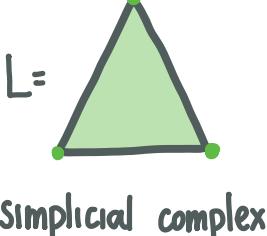


Meaningful sheaves

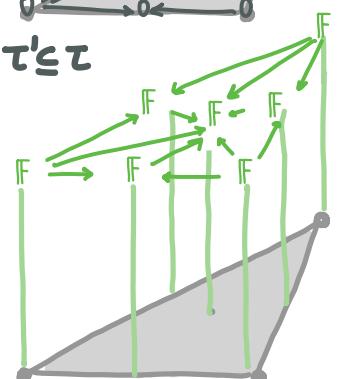
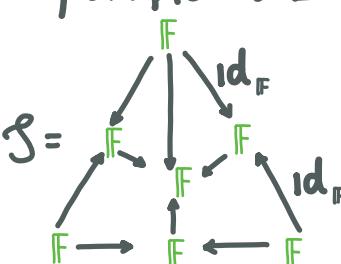
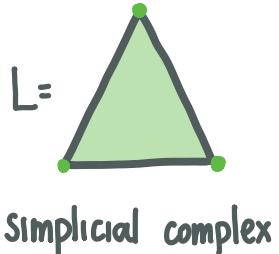
zero sheaf assigns the 0 vector space to every $\tau \in L$ and all inclusions to 0 map



skyscraper sheaf fix a simplex $\tau \in L$, assigns $\begin{cases} F & \text{to } \tau \\ 0 & \text{to } \tau' \neq \tau \end{cases}$, all inclusions to 0 map



constant sheaf F_i assigns F to every simplex $\tau \in L$ and id_F to every inclusion $\tau' \subseteq \tau$



Sheaf Cohomology

To define a cohomology, we need to define a cochain complex.
For that we need cochain groups and coboundary maps

cochain group of L with coefficients in the sheaf \mathcal{S} is the vector space

$$C^k(L; \mathcal{S}) = \prod_{\dim \tau = k} \mathcal{S}(\tau)$$

coboundary map $\partial_s^k: C^k(L; \mathcal{S}) \longrightarrow C^{k+1}(L; \mathcal{S})$ is the linear combination $\sum_{\dim \tau' = k+1} (-1)^{\dim \tau} \mathcal{S}(\tau \leq \tau')$

Proposition

The sequence $0 \longrightarrow C^0(L; \mathcal{S}) \xrightarrow{\partial_s^0} C^1(L; \mathcal{S}) \xrightarrow{\partial_s^1} \dots$ is a co-chain complex

We can define the sheaf cohomology of L with coefficients in \mathcal{S} as $H^k(L; \mathcal{S}) = \frac{\text{Ker } \partial_s^k}{\text{Im } \partial_s^{k-1}}$

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NOTE

When $\mathcal{S} = \mathbb{F}_L$ is the constant sheaf, the sheaf cohomology is the classical simplicial cohomology

Sheaves in the wild

In practice, sheaves can be considered as way to encode very complex data structures without having to build overly complex, overfitted models.

Sheaves are good, for example, to represent time-series, images, and videos.

V-sampling sheaf $\dots \leftarrow V \rightarrow 0 \leftarrow V \rightarrow 0 \leftarrow \dots$ where V a vector space

(for discrete sampling)

supported on a subset A of L is a sheaf whose stalks are V in each cell in A and 0 everywhere else

H^0 sheaf cohomology can be interpreted as the number of connected solutions / global sections of the system defined by the linear transformations + the simplicial structure

Some interesting applications

opinion dynamics / spectral theory

Robert Ghrist, Jakob Hansen

topological filters for signal processing

Georg Essl, Michael Robinson

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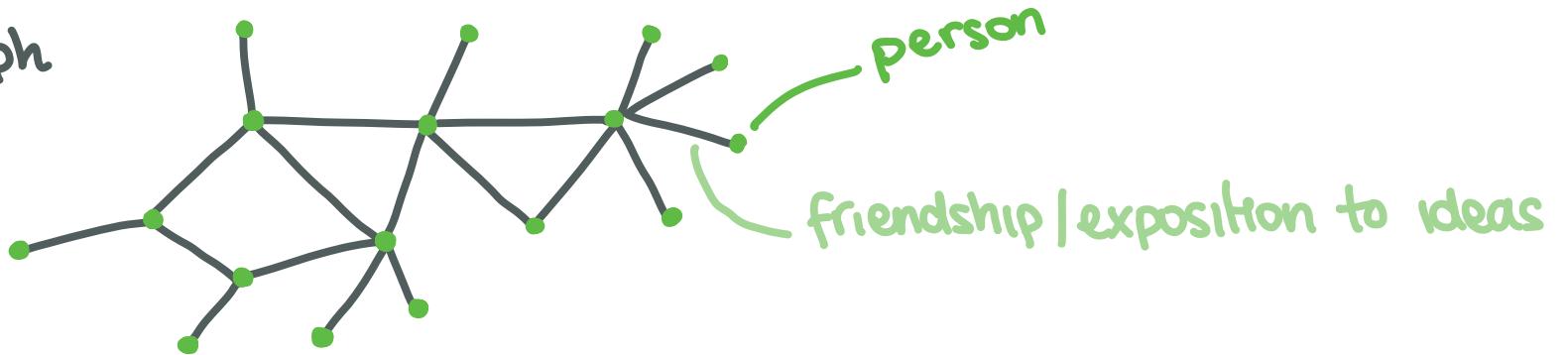
topological filters for signal processing

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Opinion Dynamics on sheaves

Jakob Hansen, Robert Ghrist

K is a graph



$C^0(K; S)$

0-chains

private opinion distribution

$C'(K; S)$

1-chains

pairwise discussion

$\partial^0: C^0 \rightarrow C'$

coboundary

aggregate of public disagreement

$L(C^0(K; S))$

laplacian

"average" of private disagreement

$H^0(K; S)$

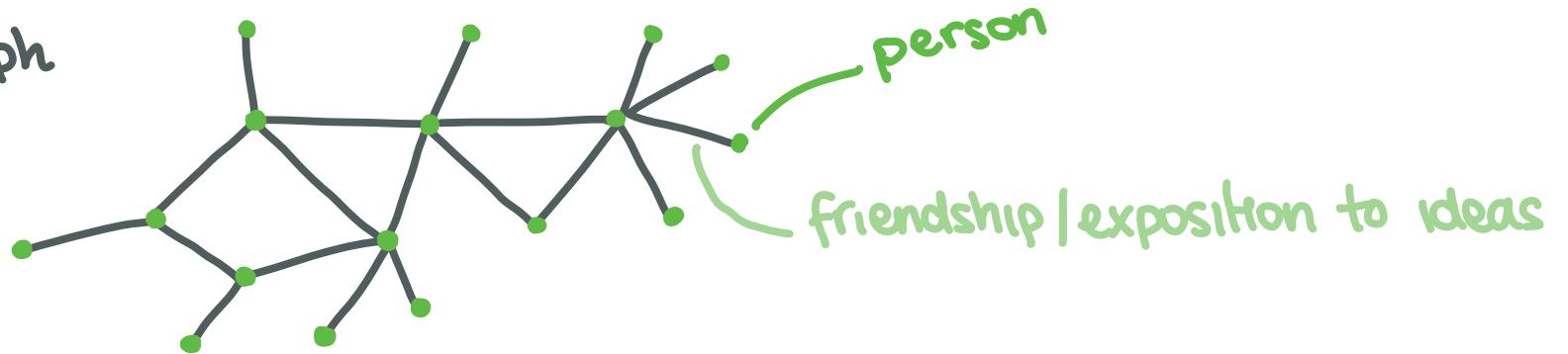
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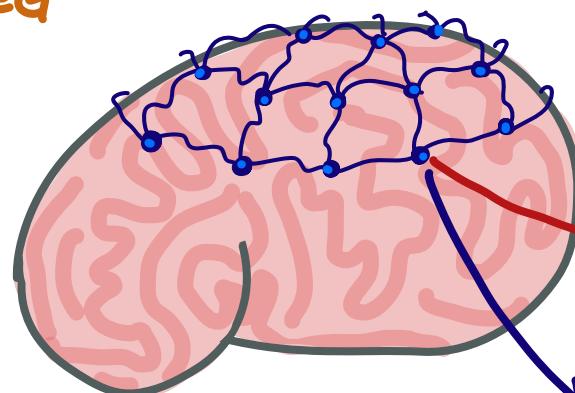
global sections

harmonic opinions
public agreement

My research

TOPOLOGY + BRAIN FUNCTION

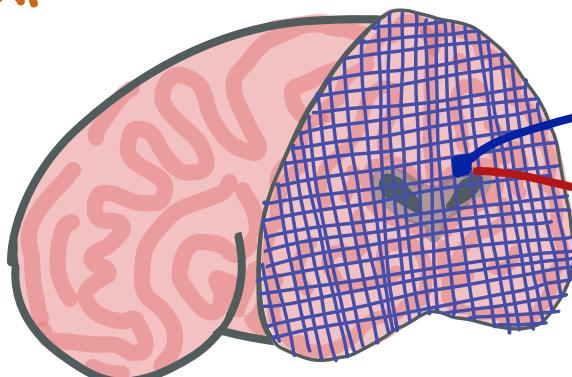
EEG



electrical current $ee \in \mathbb{R} \times \text{time} \in \mathbb{N}$

relative position in space $(x,y) \in \mathbb{R}^2$

MRI



relative position in space $(x,y,z) \in \mathbb{R}^3$

color $ce \in \mathbb{R} \times \text{time} \in \mathbb{N}$

Topological Data Analysis : getting started

ARTICLES

Persistent Homology - Theory & Practice H. Edelsbrunner and D. Morozov

Barcodes: the persistent topology of data R. Ghrist

Topology and data G. Carlsson

High-dimensional Topological Data Analysis F. Chazal

Persistence theory: from quiver representations to data analysis S. Oudot

BOOKS

Elementary Applied Topology R. Ghrist

Computational Topology: an introduction H. Edelsbrunner and J.L. Harer

Topology for computing A.J. Zomorodian

Topological Signal Processing M. Robinson

Topological Data Analysis : the community

Applied algebraic topology network Youtube channel + weekly seminar series

WinCompTop - Women in computational topology Google group + newsletter

The conferences

ATMCS = Algebraic Topology : Methods, Computations and Science every 2 years

SOCG = Symposium on Computational Geometry every year

The journals

Journal of Applied and computational topology

Homotopy, Homology and Applications

SIAM Journal of Applied Algebra and Geometry

Discrete and Computational Geometry

Foundations of computational Mathematics



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