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Fast geometric libraries for vision and data sciences

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DataShape seminar
INRIA Saclay

Who am I?

Background in **mathematics** and **data sciences**:

2012–2016 ENS Paris, mathematics.

2014–2015 M2 mathematics, vision, learning at ENS Cachan.

2016–2019 PhD thesis in **medical imaging** with Alain Trouvé at ENS Cachan.

2019–2021 **Geometric deep learning** with Michael Bronstein at Imperial College.

2021+ **Medical data analysis** in the HeKA INRIA team (Paris).

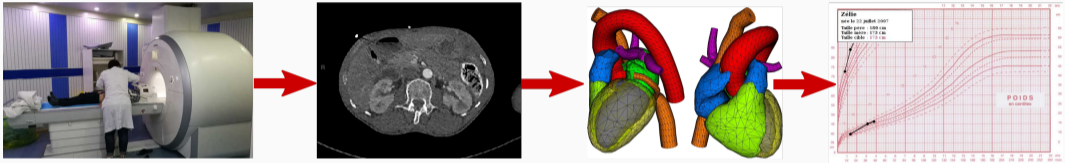
Close ties with **healthcare**:

2015 Image denoising with **Siemens Healthcare** in Princeton.

2019+ MasterClass AI–Imaging, for **radiology interns** in the University of Paris.

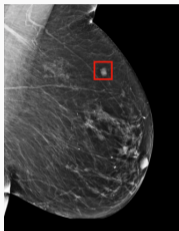
2020+ Colloquium on **Medical imaging in the AI era** at the Paris Brain Institute.

My motivation: medical data analysis

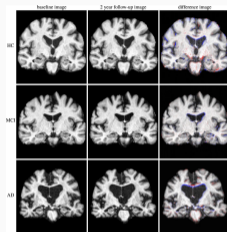


Three main characteristics:

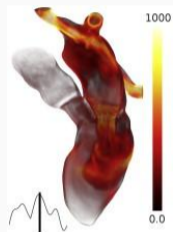
- **Heterogeneous data:** patient history, images, etc.
- Small stratified samples: 10 – 1 000 patients per group.
- Dealing with **outliers** and the **heavy tails** of our distributions is a priority.



Detect a pattern.



Analyze a variation.

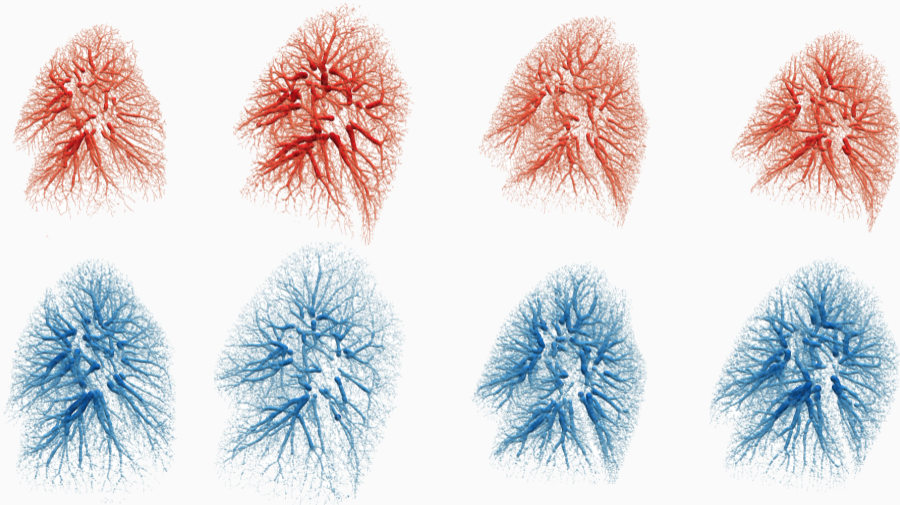


Register a model.

Some characteristics, in the wider context of computer vision research:

- **Standard acquisitions**, without occlusions.
- **Precision** work (at millimeter scale).
- Need for **guarantees** of robustness and regularity.

A typical example: lung registration “Exhale – Inhale”



Complex deformations, high resolution (50k–300k points), high accuracy ($< 1\text{mm}$).

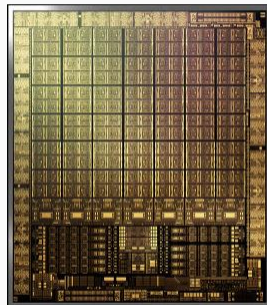
A field that is moving fast

Target. Design models that combine medical **expertise** with modern **datasets**.

Challenge. The advent of **Graphics Processing Units (GPU)**:

- Incredible **value for money**:
 $1\ 000\text{€} \simeq 1\ 000\ \text{cores} \simeq 10^{12}\ \text{operations/s}$.
- **Bottleneck**: constraints on **register** usage.

“User-friendly” Python ecosystem, consolidated around a **small number of key operations**.



7,000 cores
in a single GPU.

My project: a long-term investment in the foundations of our field

Solution. Expand the **standard toolbox** in data sciences to deal with the challenges of the healthcare industry.

Ease the development of **advanced models**, without compromising on numerical performance.

In-depth work, numerical **foundations** → **high-level** applications:

1. Efficient manipulation of “**symbolic**” **matrices** (distances, kernel, etc.).
2. **Optimal transport**: generalized sorting methods.
3. Geometric **deep learning**.

Discussion about the **future** of these tools and **clinical** perspectives.

1. Symbolic matrices

Computing libraries represent most objects as tensors

Context. Constrained **memory accesses** on the GPU:

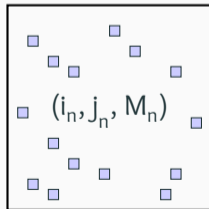
- **Long access times** to the registers penalize the use of large **dense** arrays.
- Hard-wired **contiguous** memory accesses penalize the use of **sparse** matrices.

Challenge. In order to reach optimal run times:

- **Restrict** ourselves to operations that are supported by the constructor: convolutions, FFT, etc.
- Develop new routines from scratch in C++/CUDA (FAISS, KPCConv...): **several months of work.**



Dense array



Sparse matrix

The KeOps library: efficient support for symbolic matrices

Solution. KeOps – www.kernel-operations.io:

- For PyTorch, NumPy, Matlab and R, on **CPU and GPU**.
- **Automatic differentiation**.
- Just-in-time **compilation** of **optimized C++** schemes, triggered for every new **reduction**: sum, min, etc.

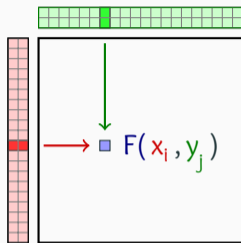
If the formula “F” is simple (≤ 100 arithmetic operations):

“100k \times 100k” computation \rightarrow 10ms – 100ms,

“1M \times 1M” computation \rightarrow 1s – 10s.

Hardware ceiling of 10^{12} operations/s.

$\times 10$ to $\times 100$ **speed-up** vs standard GPU implementations
for a wide range of problems.



Symbolic matrix

Formula + data

- Distances $d(x_i, y_j)$.
- Kernel $k(x_i, y_j)$.
- Numerous transforms.

A first example: efficient nearest neighbor search in dimension 50

Create large point clouds using **standard PyTorch syntax**:

```
import torch
N, M, D = 10**6, 10**6, 50
x = torch.rand(N, 1, D).cuda() # (1M, 1, 50) array
y = torch.rand(1, M, D).cuda() # (1, 1M, 50) array
```

Turn **dense** arrays into **symbolic** matrices:

```
from pykeops.torch import LazyTensor
x_i, y_j = LazyTensor(x), LazyTensor(y)
```

Create a large **symbolic matrix** of squared distances:

```
D_ij = ((x_i - y_j) ** 2).sum(dim=2) # (1M, 1M) symbolic
```

Use an `.argmin()` **reduction** to perform a nearest neighbor query:

```
indices_i = D_ij.argmin(dim=1) # -> standard torch tensor
```

The KeOps library combines performance with flexibility

Script of the previous slide = efficient nearest neighbor query,
on par with the bruteforce CUDA scheme of the **FAISS** library...

And can be used with **any metric!**

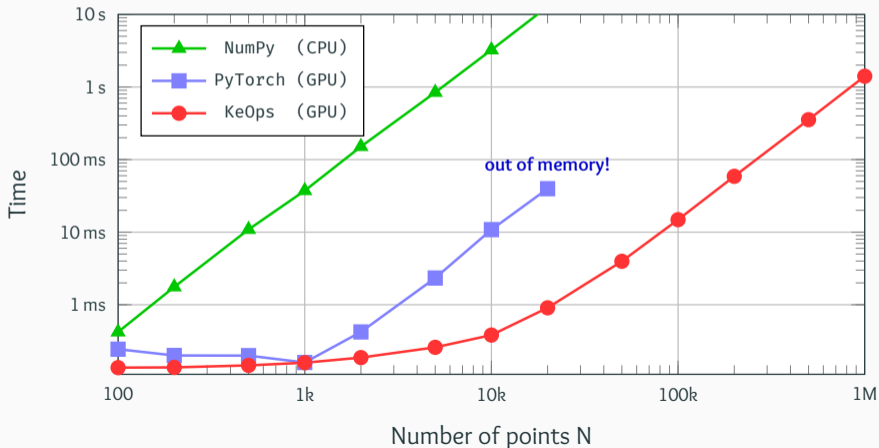
```
D_ij = ((x_i - x_j) ** 2).sum(dim=2)      # Euclidean
M_ij = (x_i - x_j).abs().sum(dim=2)     # Manhattan
C_ij = 1 - (x_i | x_j)                  # Cosine
H_ij = D_ij / (x_i[...,0] * x_j[...,0]) # Hyperbolic
```

KeOps supports arbitrary **formulas** and **variables** with:

- **Reductions:** sum, log-sum-exp, K-min, matrix-vector product, etc.
- **Operations:** +, ×, sqrt, exp, neural networks, etc.
- **Advanced schemes:** batch processing, block sparsity, etc.
- **Automatic differentiation:** seamless integration with PyTorch.

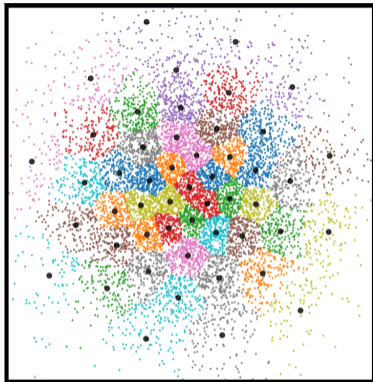
KeOps lets users work with millions of points at a time

Benchmark of a Gaussian **convolution**
between **clouds of N 3D points** on a RTX 2080 Ti GPU.



Applications

KeOps is a good fit for machine learning research



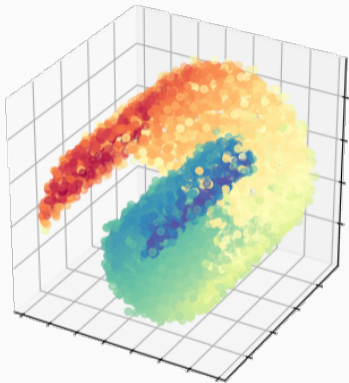
K-Means.



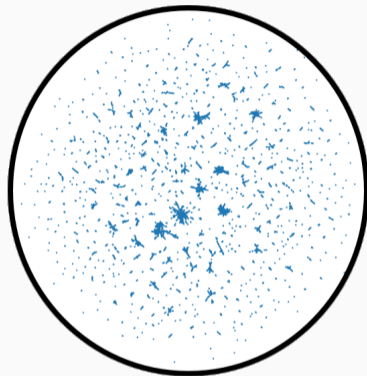
Gaussian Mixture Model.

Use **any** kernel, metric or formula **you** like!

KeOps is a good fit for machine learning research



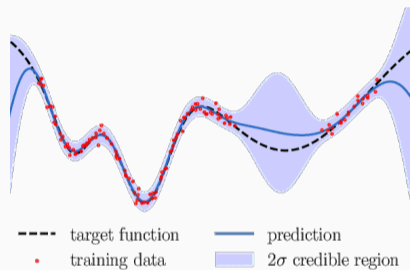
Spectral analysis.



UMAP in hyperbolic space.

Use **any** kernel, metric or formula **you** like!

A standard tool for regression [Lec18]:



Under the hood, solve a **kernel linear system**:

$$(\lambda \text{Id} + K_{xx}) a = b \quad \text{i.e.} \quad a \leftarrow (\lambda \text{Id} + K_{xx})^{-1} b$$

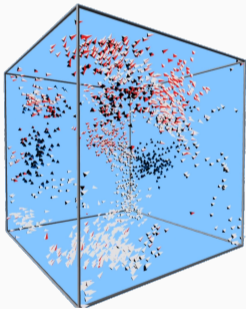
where $\lambda \geq 0$ et $(K_{xx})_{i,j} = k(x_i, x_j)$ is a positive definite matrix.

KeOps symbolic tensors $(K_{xx})_{i,j} = k(x_i, x_j)$:

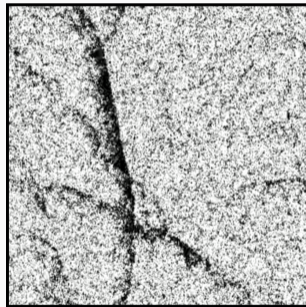
- Can be fed to **standard solvers**: SciPy, GPyTorch, etc.
- GPytorch on the 3DRoad dataset (N = 278k, D = 3):
7h with 8 GPUs → **15mn with 1 GPU.**
- Provide a **fast backend for research codes**:
see e.g. *Kernel methods through the roof: handling **billions of points** efficiently*,
by G. Meanti, L. Carratino, L. Rosasco, A. Rudi (2020).

KeOps lets you focus on your models, results and theorems

Some applications to **dynamical systems** [DM08, DFMAT17]
and **statistics** [CDF19] with A. Diez, G. Clarté et P. Degond:



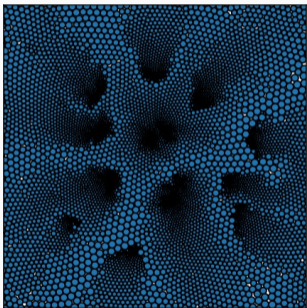
3D Vicsek model with orientation,
interactive demo with 2k **flyers**.



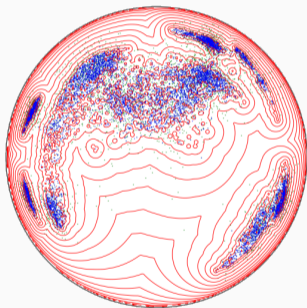
2D Vicsek model on the torus,
in real-time with 100k **swimmers**.

KeOps lets you focus on your models, results and theorems

⇒ Scale up to **millions/billions** of agents with Python scripts.



Packing problem in 2D
with 10k repulsive balls.



Collective Monte Carlo **sampling**
on the hyperbolic Poincaré disk.

2. Back to shapes: optimal transport

Optimal transport (OT) generalizes sorting to spaces of dimension $D > 1$

Context. If $A = (x_1, \dots, x_N)$ and $B = (y_1, \dots, y_N)$ are two clouds of N points in \mathbb{R}^D , we define:

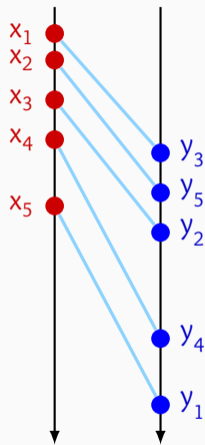
$$\text{OT}(A, B) = \min_{\sigma \in \mathcal{S}_N} \frac{1}{2N} \sum_{i=1}^N \|x_i - y_{\sigma(i)}\|^2$$

Generalizes **sorting** to metric spaces.

Linear problem on the permutation matrix P :

$$\text{OT}(A, B) = \min_{P \in \mathbb{R}^{N \times N}} \frac{1}{2N} \sum_{i,j=1}^N P_{i,j} \cdot \|x_i - y_j\|^2,$$

$$\text{s.t. } P_{i,j} \geq 0 \quad \underbrace{\sum_j P_{i,j} = 1}_{\text{Each source point...}} \quad \underbrace{\sum_i P_{i,j} = 1}_{\text{is transported onto the target.}}$$



assignment
 $\sigma : [1, 5] \rightarrow [1, 5]$

Key properties of this distance “up to permutations”

The Wasserstein distance $\sqrt{\text{OT}}(\mathbf{A}, \mathbf{B})$ is:

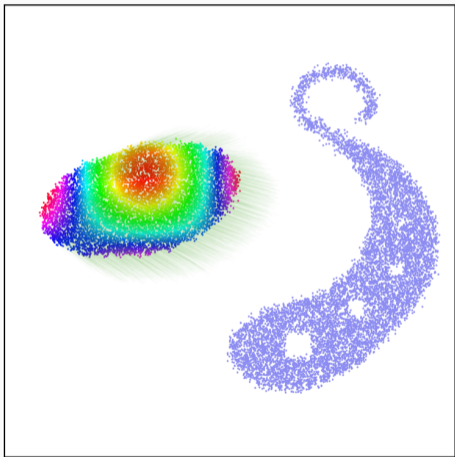
- **Symmetric:** $\text{OT}(\mathbf{A}, \mathbf{B}) = \text{OT}(\mathbf{B}, \mathbf{A})$.
- **Positive:** $\text{OT}(\mathbf{A}, \mathbf{B}) \geq 0$.
- **Definite:** $\text{OT}(\mathbf{A}, \mathbf{B}) = 0 \iff \mathbf{A} = \mathbf{B}$.
- **Translation-aware:** $\text{OT}(\mathbf{A}, \text{Translate}_{\vec{v}}(\mathbf{A})) = \frac{1}{2} \|\vec{v}\|^2$.
- More generally, OT retrieves the unique **gradient of a convex function** $T = \nabla \phi$ that maps \mathbf{A} onto \mathbf{B} :

$$\text{In dimension 1, } (\mathbf{x}_i - \mathbf{x}_j) \cdot (\mathbf{y}_{\sigma(i)} - \mathbf{y}_{\sigma(j)}) \geq 0$$

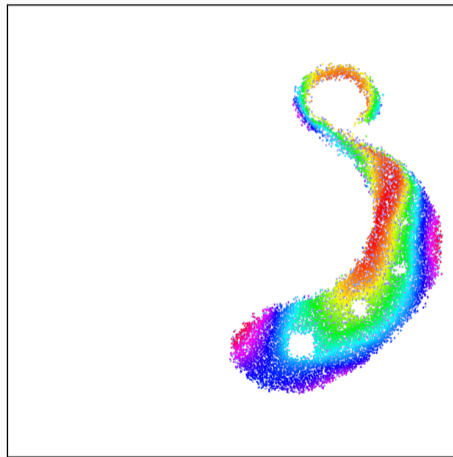
$$\text{In dimension D, } \langle \mathbf{x}_i - \mathbf{x}_j, T(\mathbf{x}_i) - T(\mathbf{x}_j) \rangle_{\mathbb{R}^D} \geq 0.$$

\implies Appealing generalization of an **increasing mapping**.

An efficient model... but beware of tears!

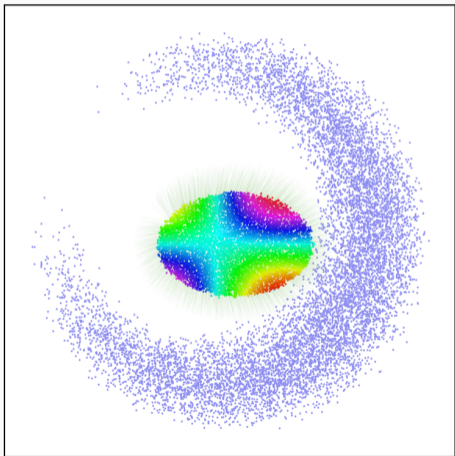


Before

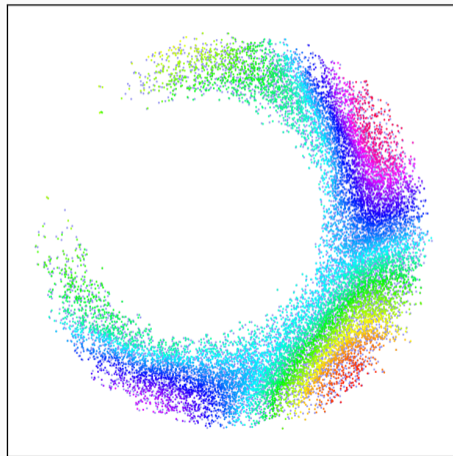


After

An efficient model... but beware of tears!

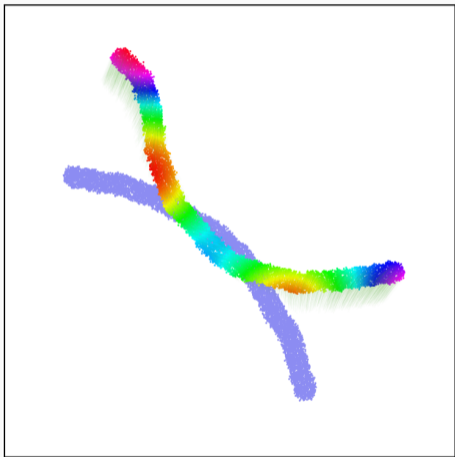


Before

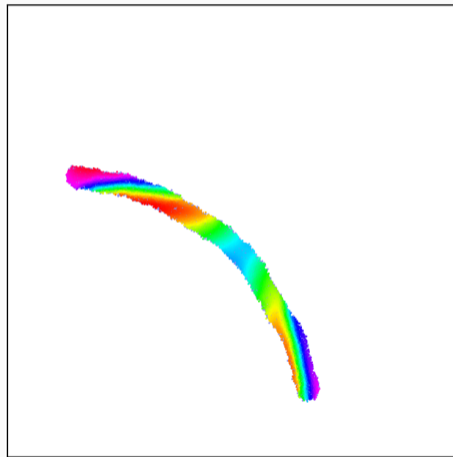


After

An efficient model... but beware of tears!

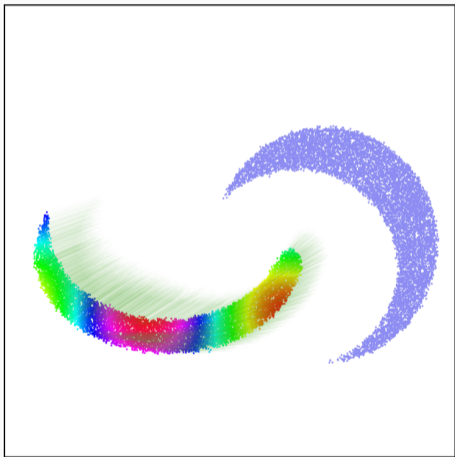


Before

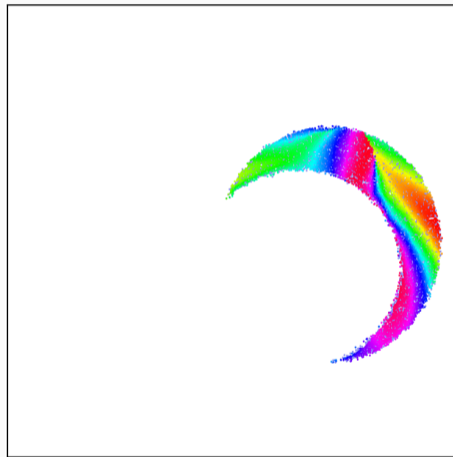


After

An efficient model... but beware of tears!



Before



After

How should we solve the OT problem?

Key dates for discrete optimal transport with N points:

- [Kan42]: **Dual** problem of Kantorovitch.
- [Kuh55]: **Hungarian** methods in $O(N^3)$.
- [Ber79]: **Auction** algorithm in $O(N^2)$.
- [KY94]: **SoftAssign** = Sinkhorn + simulated annealing, in $O(N^2)$.
- [GRL⁺98, CR00]: **Robust Point Matching** = Sinkhorn as a loss.
- [Cut13]: Start of the **GPU era**.
- [Mér11, Lév15, Sch19]: **multi-scale** solvers in $O(N \log N)$.

- **Solution**, today: **Multiscale Sinkhorn algorithm, on the GPU.**
 \implies Generalized **QuickSort** algorithm.

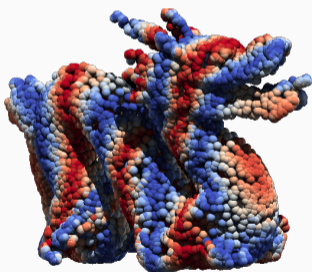
Scaling up optimal transport to anatomical data

Progresses of the last decade add up to a $\times 100$ - $\times 1000$ acceleration:

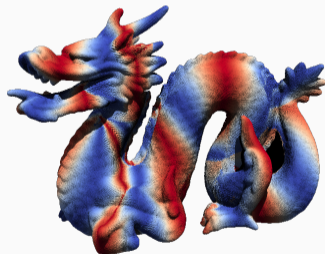
Sinkhorn GPU $\xrightarrow{\times 10}$ + KeOps $\xrightarrow{\times 10}$ + Annealing $\xrightarrow{\times 10}$ + Multi-scale

With a precision of 1%, on a modern gaming GPU:

`pip install`
`geomloss`
+
modern GPU
(1 000 €)



10k points in 30-50ms



100k points in 100-200ms

3. Geometric deep learning

Design task-specific trainable models

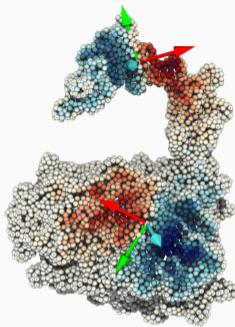
Context. Trainable models on **non-Euclidean domains** (point clouds, surfaces, graphs, etc.), beyond 2D/3D images.

Challenge. In spite of growing interest in the industry, these models still **lack support** on the numerical side. C++/CUDA is (often) required to reach top performance.

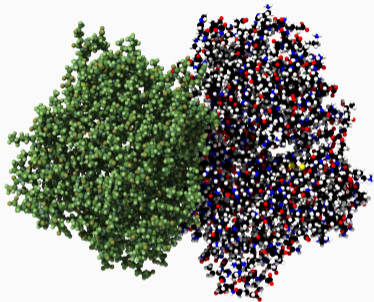
Solution. Using KeOps, with a few lines of Python:

- **Local** interactions: K-nearest neighbors.
- **Global** interactions: generalized convolutions.

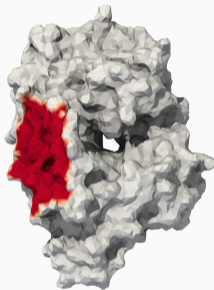
Modelling **freedom**
⇒ **Domain-specific** priors.



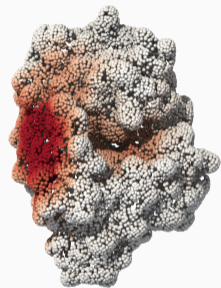
Quasi-geodesic convolution on a protein surface.



(a) Raw protein data.

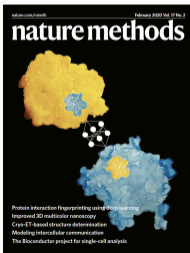
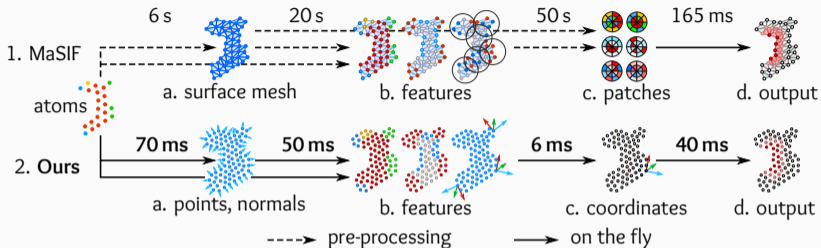


(b) Interface.



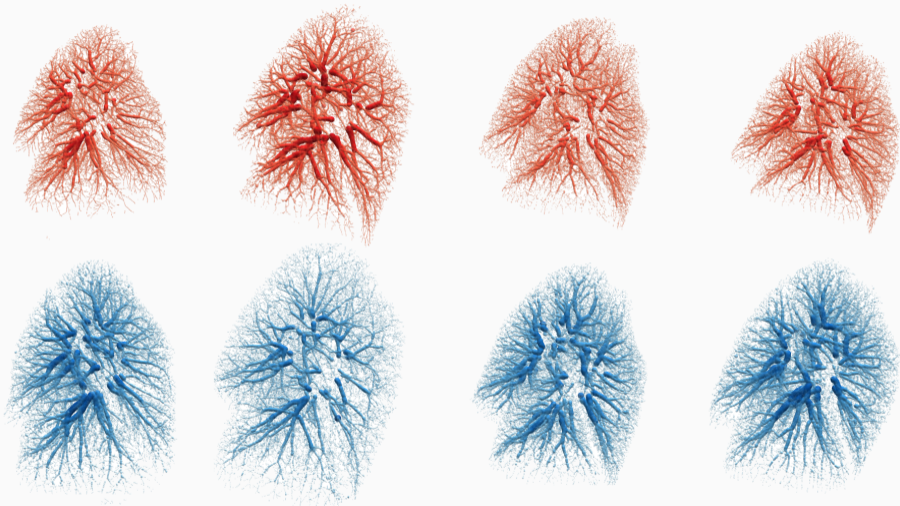
(c) Prediction.

Fast end-to-end learning on protein surfaces



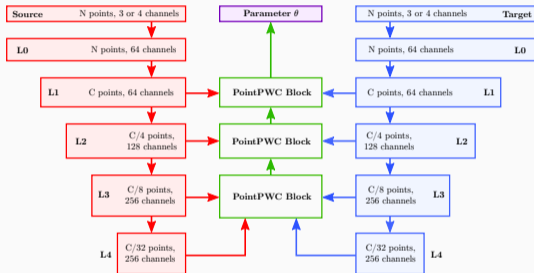
→ ×100-×1,000 faster, lighter and fully differentiable.

Lung registration “Exhale – Inhale”



Complex deformations, high resolution (50k–300k points), high accuracy ($< 1\text{mm}$).

State-of-the-art networks – and their limitations



Multi-scale convolutional
point neural network.

Point neural nets, in practice:

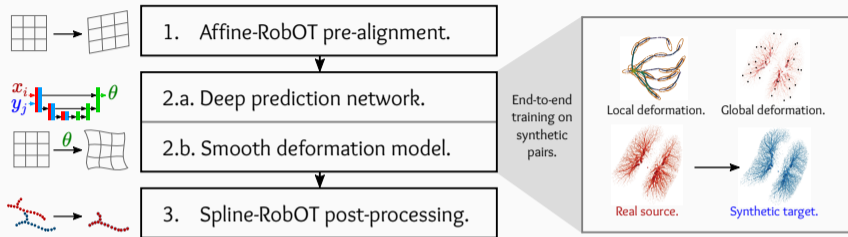
- Compute **descriptors** at all scales.
- **Match** them using geometric layers.
- Train on **synthetic** deformations.

Strengths and weaknesses:

- Good at **pairing** branches.
- Hard to train to high **accuracy**.

⇒ **Complementary** to OT.

Three-steps registration

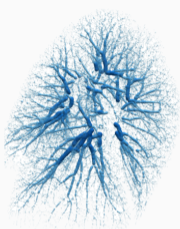


This **pragmatic** method:

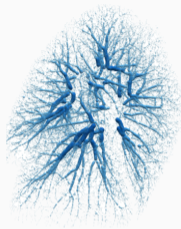
- Is **easy to train** on synthetic data.
- Scales up to high-resolution: 100k points in 1s.
- Excellent results: **KITTI** (outdoors scans) and **DirLab** (lungs).

*Accurate point cloud registration with **robust** optimal transport,*
Shen, Feydy et al., NeurIPS 2021.

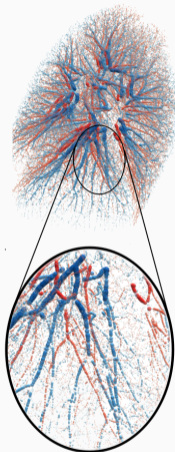
Three-steps registration



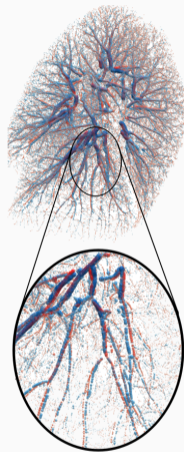
0. Input data



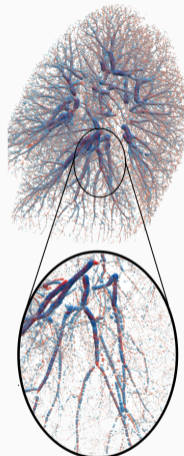
1. Pre-alignment



Zoom !



2. Deep registration



3. Fine-tuning

Conclusion

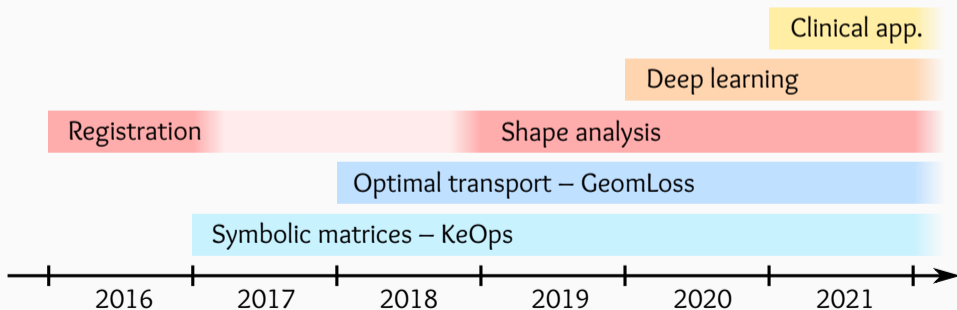
Key points

- **Symbolic** matrices are to **geometric** ML what **sparse** matrices are to **graph** processing:
 - KeOps: **x30 speed-up** vs. PyTorch, TF et JAX.
 - Useful in a wide range of settings.
- Optimal Transport = **generalized sorting** :
 - Simple registration for shapes that are close to each other.
 - Super-fast $O(N \log N)$ solvers.
- These tools open **new paths** for geometers and statisticians:
 - GPUs are more **versatile** than you think.
 - Ongoing work to provide **fast GPU backends** to researchers, going beyond what Google and Facebook are ready to pay for.

Summary: a long-term investment that is starting to bear fruits

Two major evolutions:

- “Big” geometric problem: $N > 10k \rightarrow N > 1M$.
- Optimal transport: linear **problem** + generalized **quicksort**.



Genuine team work



Alain Trouvé



Thibault Séjourné



F.-X. Vialard



Gabriel Peyré



Benjamin Charlier



Joan Glaunès



Freyr Sverrisson



Shen Zhengyang

+ Marc Niethammer, Bruno Correia, Michael Bronstein...

The talk today was primarily about **3D data**.

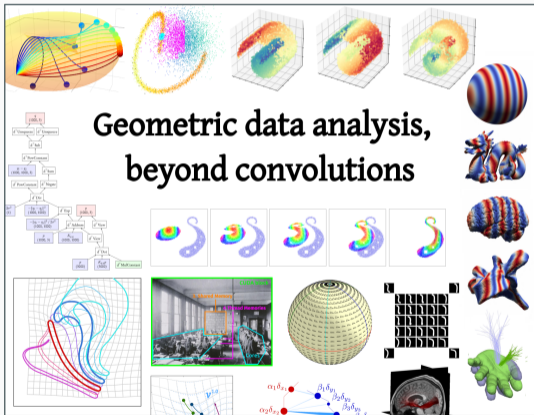
This has been my main focus since 2016.

However, I am now embedded in a medical team that has a strong expertise in **public health** and **pharmaceutical problems**.
(Spreadsheets! Time series! Cartes vitales!)

Studying geometric methods in **high-dimensional** scenarios is one of my top priorities for the next five years.

I'll be happy to discuss this with you today, tomorrow and later :-)

⇒ www.kernel-operations.io ⇐



References

 Dimitri P Bertsekas.

A distributed algorithm for the assignment problem.

Lab. for Information and Decision Systems Working Paper, M.I.T., Cambridge, MA, 1979.

 Grégoire Clarté, Antoine Diez, and Jean Feydy.

Collective proposal distributions for nonlinear MCMC samplers: Mean-field theory and fast implementation.

arXiv preprint arXiv:1909.08988, 2019.

 Christophe Chnafa, Simon Mendez, and Franck Nicoud.

Image-based large-eddy simulation in a realistic left heart.

Computers & Fluids, 94:173–187, 2014.

 Haili Chui and Anand Rangarajan.

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