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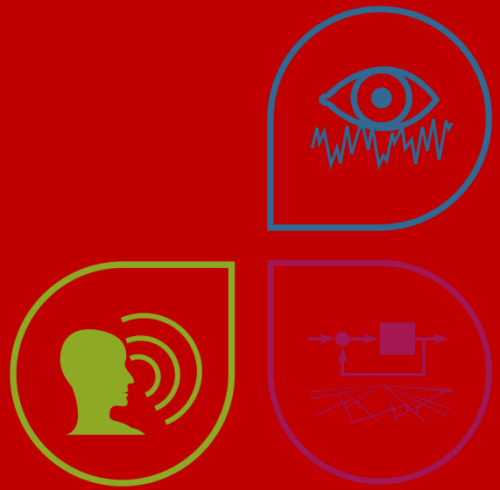
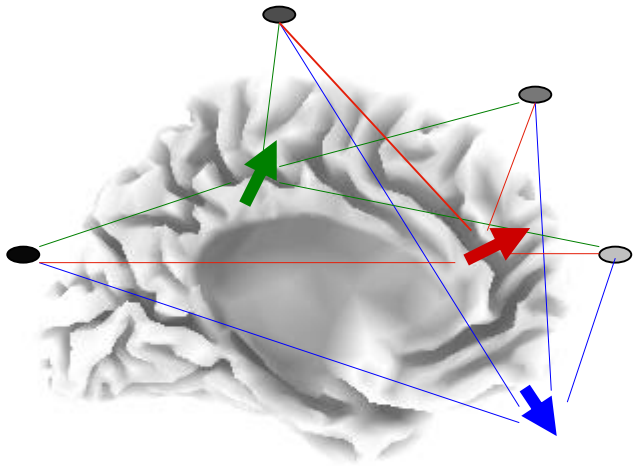


Riemannian Geometry for BCIs:

Intuition and Theory

Generative Model of EEG



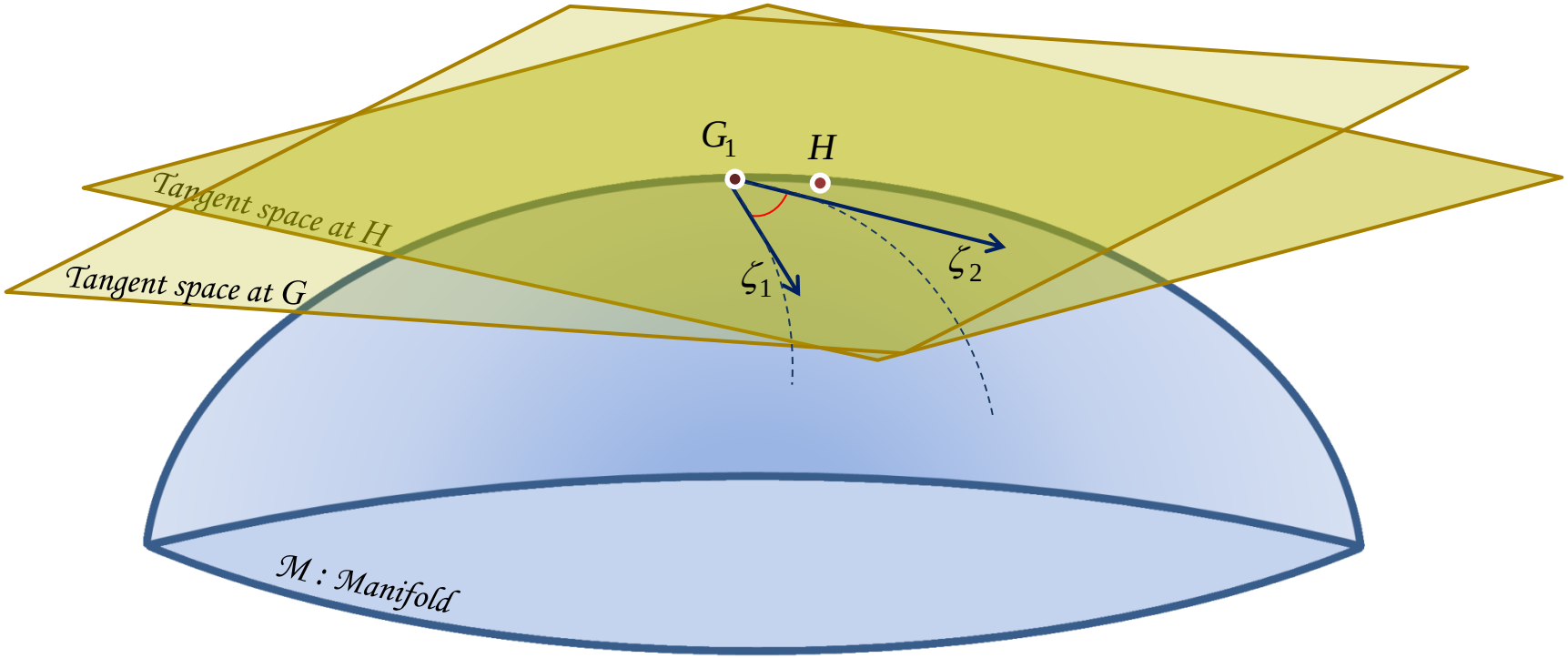
X — *N* sensor measurements

S — *P*≤*N* source dipolar fields

$$X = AS \longrightarrow Cov(X) = A\,Cov(S)\,A^T$$

Constant for a given task

Riemannian Geometry of Covariance Matrices



The tangent space at point G is the Euclidean vector space containing the tangent vectors to all curves on $\mathcal{M}$ passing through G.

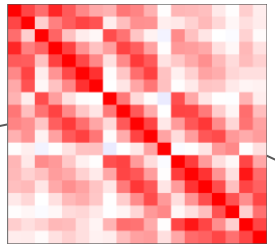
Inner product on tangent space (metric) → Riemannian Manifold

Fisher Metric of the SPD Manifold: $\mathrm{tr}\left(G^{-1}\zeta_1 G^{-1}\zeta_2\right)$

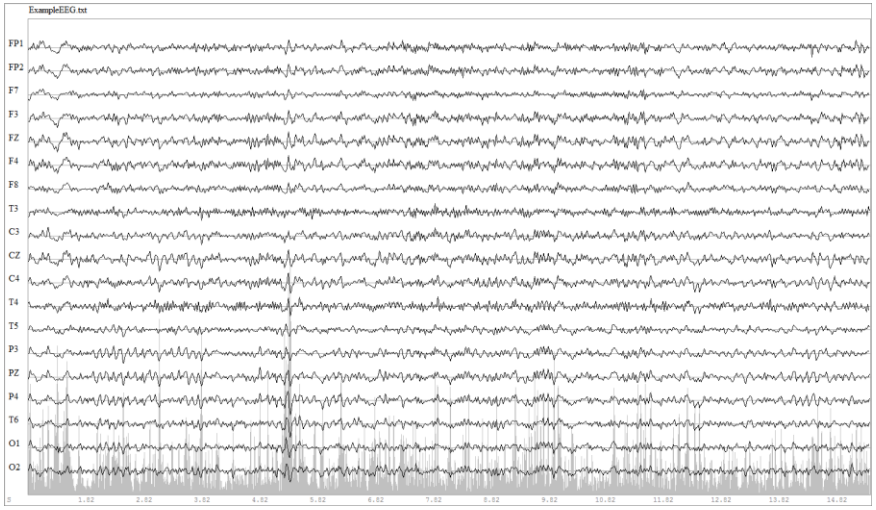
Norm: $\left\|G^{-1}\zeta\right\|_F$

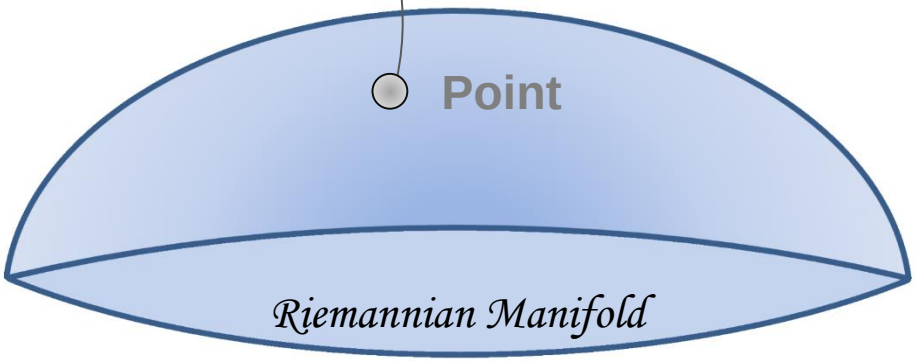
Mapping EEG data on the Manifold of SPD matrices

Covariance matrix

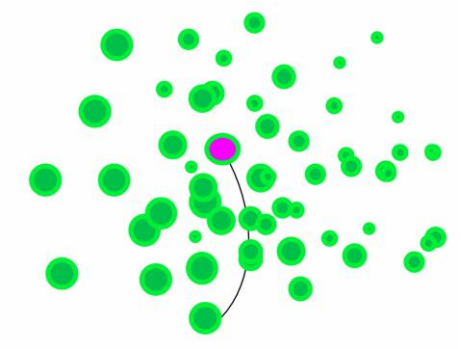


EEG Data

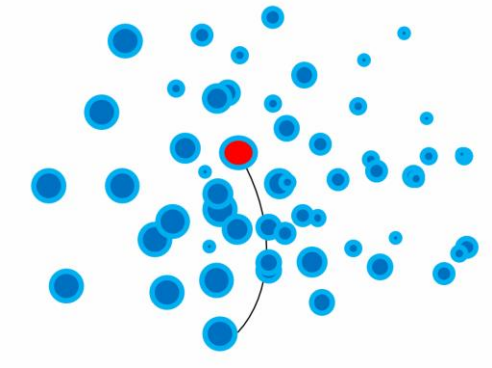




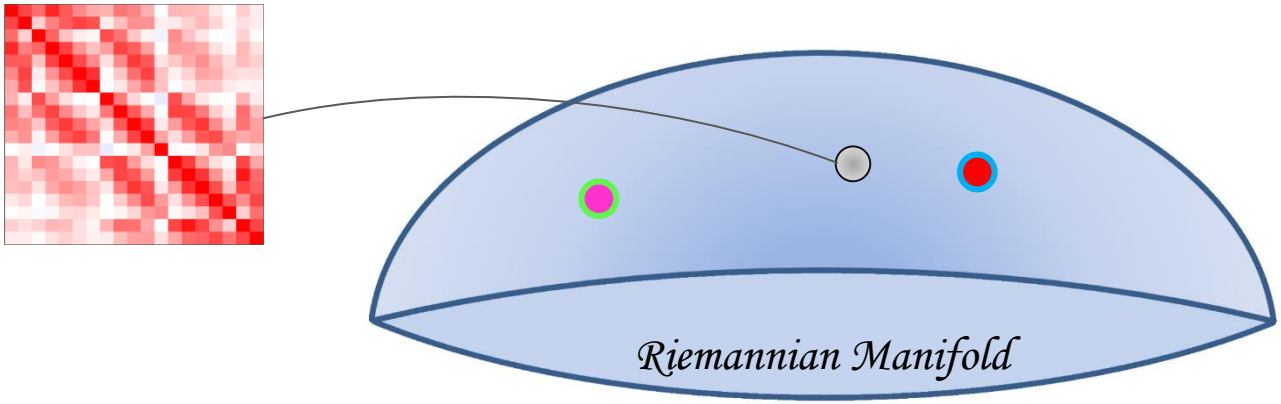
Minimum Distance to Mean (MDM) Classifier



Class 1



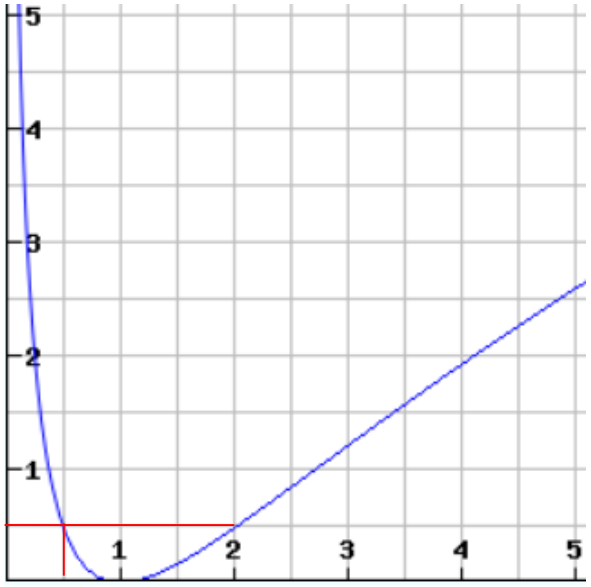
Class 2



The Fisher-Rao distance

$$\delta^2\left(C_1, C_2\right) = \sum\nolimits_n \log^2 \lambda_n \left(C_1^{-1} C_2\right)$$

$y = \log^2(x)$



Invariances

Congruence (Affine) $\quad \delta\left(C_1,\ C_2\right) = \delta\left(BC_1B^T,\ BC_2B^T\right)$

Inversion (Self-Duality) $\quad \delta\left(C_1,\ C_2\right) = \delta\left(C_1^{-1},\ C_2^{-1}\right)$

Congruence Invariance

(equivalence of sensor and source space)

First Order

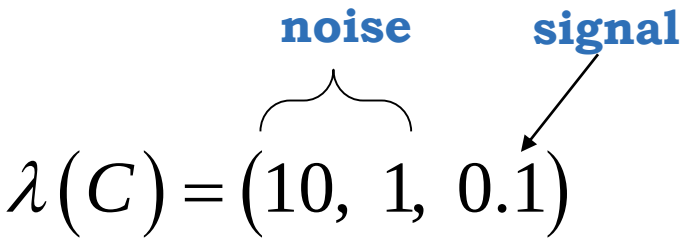
$$X = AS$$

Second Order

$$\mathrm{cov}\left(X\right) = A\,\mathrm{cov}\left(S\right)A^{T}$$

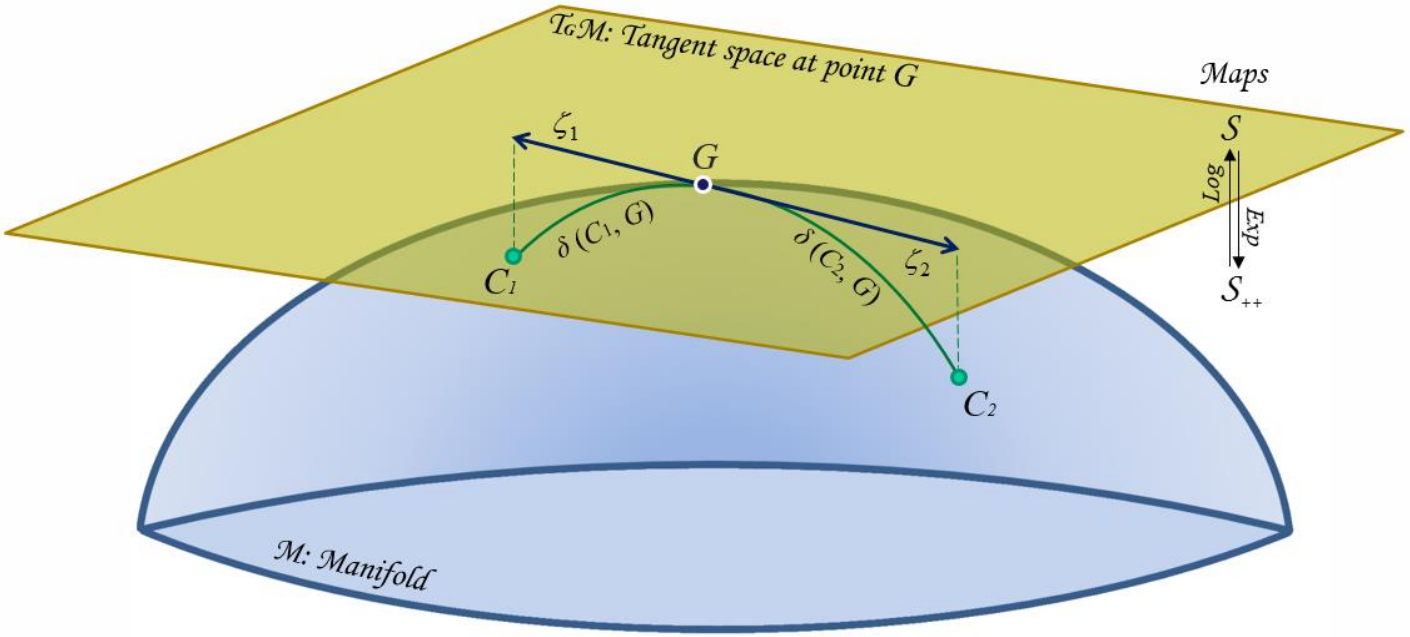
Inversion Invariance

(adjust to heterogeneity of source power)



$$\lambda\left(C^{-1}\right) = (0.1,\ 1,\ 10)$$

The PD Geodesic (t-weighted mean)



$$C_1 \#_t C_2 = C_1^{1/2}\left(C_1^{-1/2} C_2 C_1^{-1/2}\right)^t C_1^{1/2}, \qquad t \in [0,1]$$

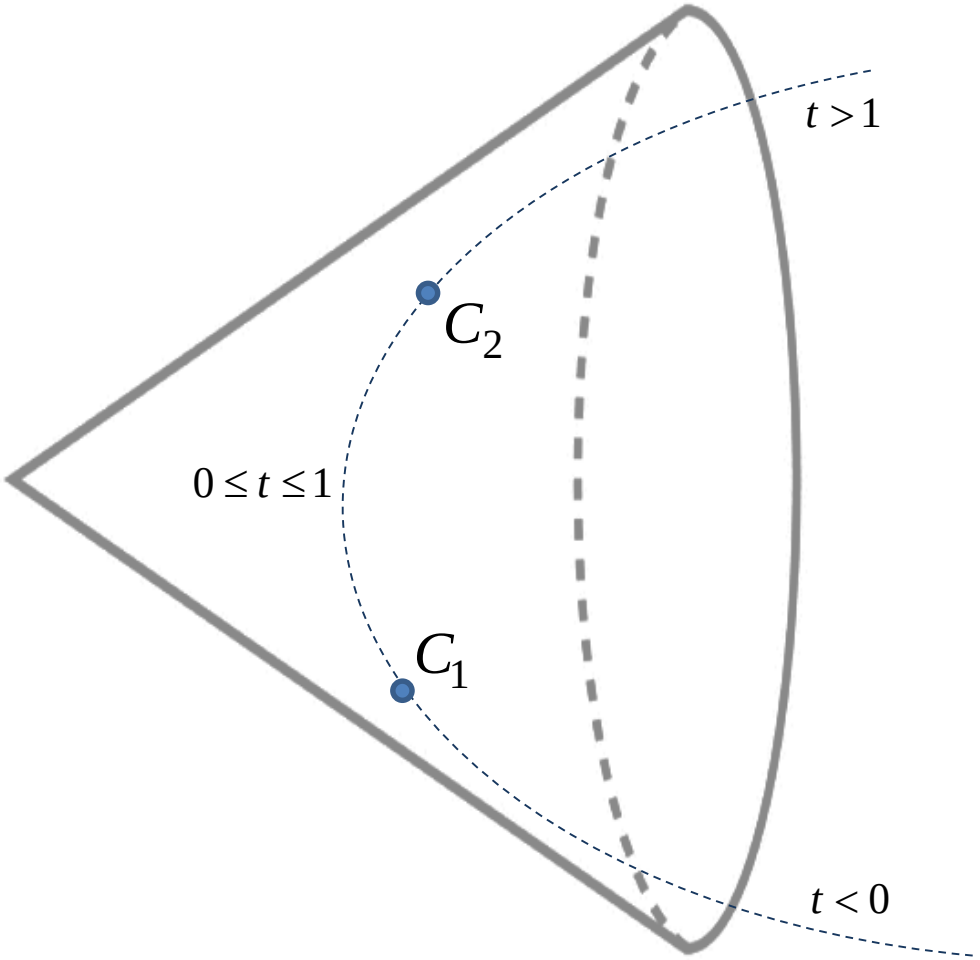
$$C_1 \#_0 C_2 = C_1$$

$$C_1 \#_1 C_2 = C_2$$

$$C_1 \#_{1/2} C_2 = G \quad \text{(Midpoint = } \textit{Geometric Mean}\text{)}$$

Bhatia (2007) Positive Definite Matrices, Princeton press.

Interpolation & Extrapolation

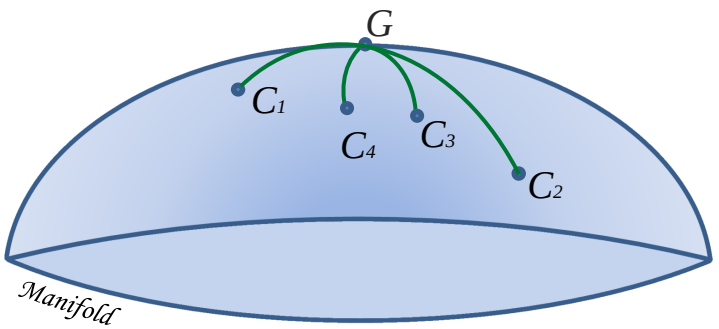


$$C_1 \#_t C_2 = C_1^{1/2} \left(C_1^{-1/2} C_2 C_1^{-1/2} \right)^t C_1^{1/2}$$

Geometric Mean

(Karcher mean, Barycenter, Centre of Mass…)

$$\arg\min_{G} \sum_k \delta^2\left(G, C_k\right)$$

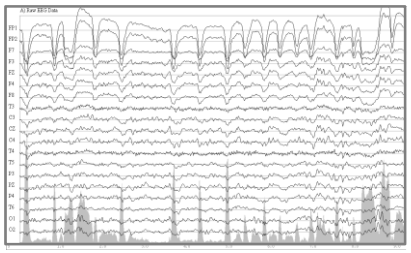


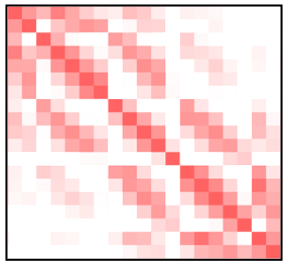
Always exixts, is unique and satisfies $\sum_k \left[\operatorname{Log}\left(G^{-1/2} C_k G^{-1/2}\right)\right] = 0$

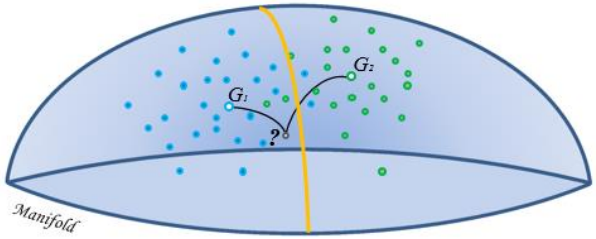
Existence and uniqueness first proved by Elie Cartan on Lie groups

Moakher M (2005) SIAM. J. Matrix Anal. Appl, 26 (3), 735-747.

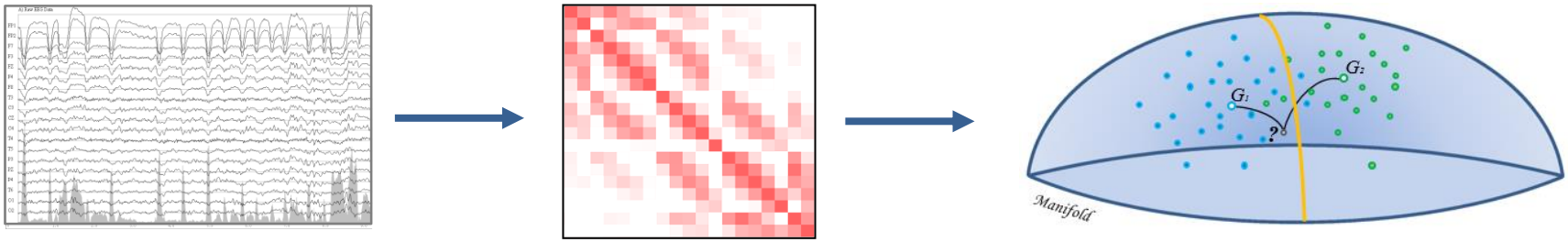
ML on Manifold



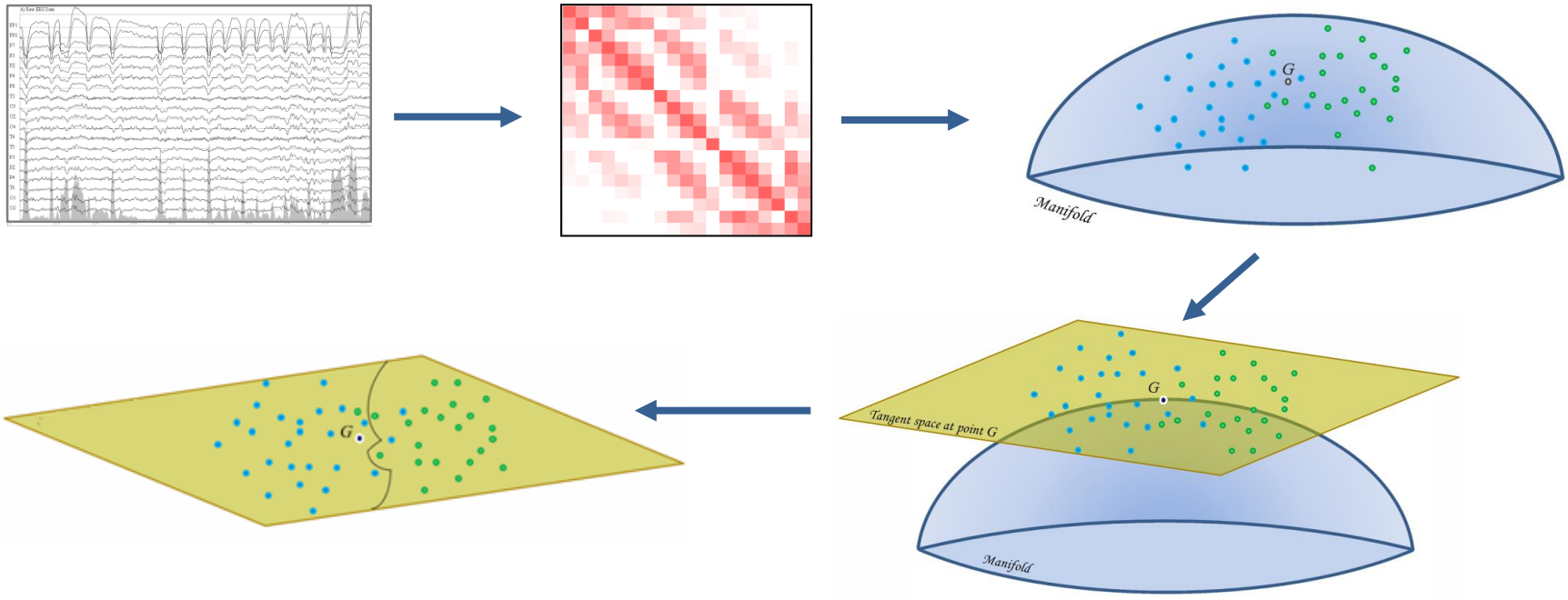




ML on Manifold



ML on Tangent Space



International BCI Decoding Competitions

Nom de la Compétition	Événement ou Organisateur	Clôture	Participants	Score (%)
DecMeg 2014	BIOMAG 2014 Conference	27/07/2014	301	75.5
BCI Challenge	IEEE NER 2015 Conference	24/02/2015	311	87.2
Grasp&Lift EEG Challenge	WAY European Project	31/08/2015	452	98.1
Decoding Brain Signals	Microsoft	01/07/2016	688	93.7
Biomag2016 competition	BIOMAG 2016 Conference	25/09/2016	7	95.6

Congedo, Bhatia & Barachant (2017)
Riemannian Geometry for EEG-based Brain-Computer Interfaces; a Primer and a Review.
Brain-Computer Interfaces, 4(3), 155-174.

Code for Riemannian geometry

(**Julia –** Python – R – Matlab – C++ – Delphi)

https://sites.google.com/site/marcocongedo/science/code-resources

P300-BCI Data

https://sites.google.com/site/marcocongedo/science/EEG-data

7 *Databases*

273 *Subjects*

1446 *Sessions*

BCI in Virtual Reality and on a PC

Description: Visual P300 BCI experiment on PC and virtual reality (passive head-mounted display) (2018)
Subjects: 21
Sessions: 2
Electrodes: 16 wet Silver/Silver Chloride electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *VR.EEG.2018-GIPSA*

Brain Invaders Multi-User Cooperation vs. Competition

Description: Multi-User Brain Invaders: Cooperation versus Competition condition (2015)
Subjects: 44
Sessions: 2
Electrodes: 32 wet Silver/Silver Chloride electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *bi2015b*

Brain Invaders Multi-User flash duration

Description: Brain Invaders calibration-less P300-based BCI with modulation of flash duration (2015)
Subjects: 50
Sessions: 3
Electrodes: 32 wet Silver/Silver Chloride electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *bi2015a*

Brain Invaders Solo vs. Multi-User Collaboration

Description: Multi-User Brain Invaders in Solo versus Collaboration condition (2014)
Subjects: 38
Sessions: 3
Electrodes: 32 wet Silver/Silver Chloride electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *bi2014b*

Brain Invaders dry electrodes

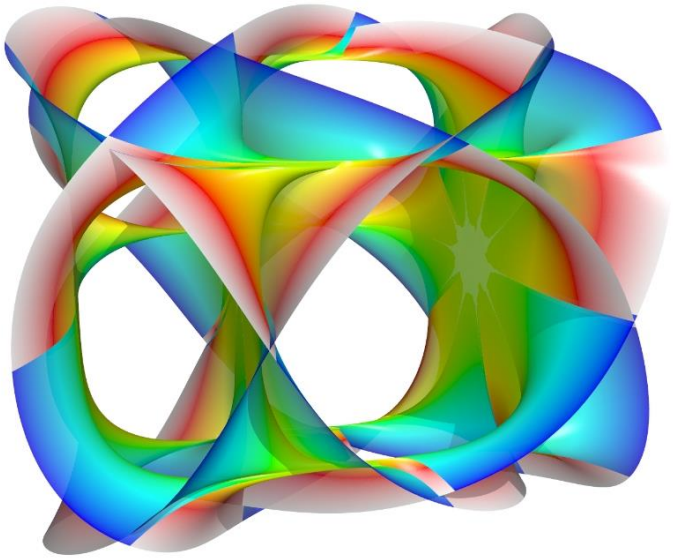
Description: Brain Invaders calibration-less P300-based BCI with dry electrodes (2014)
Subjects: 71
Sessions: up to three per participant
Electrodes: 16 metal dry electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *bi2014a*

Brain Invaders Adaptive vs. Non-Adaptive

Description: First Brain Invaders dataset of a BCI working without calibration (2013)
Subjects: 24
Sessions: 8 for subjects 1-7, one for the remaining.
Electrodes: 16 wet Silver/Silver Chloride electrodes
EEGMachine: g.tec g.USBamp
Sampling Rate: 512 sps
Database ID: *BI.EEG.2013-GIPSA*

Building Brain Invaders

Description: First Brain Invaders BCI dataset (2012)
Subjects: 25
Sessions: 2
Electrodes: 16 wet Silver/Silver Chloride electrodes
EEG Machine: TMSI Porti
Sampling Rate: 128 sps
Database ID: *BI.EEG.2012-GIPSA*



Collaborators @GIPSA-lab

Prof. C. Jutten

Ingeneer: A. Andreev

Post-Doc: A. Barachant, P. Zanini

PhD Students: L. Korczowski, F. Barachant, P.L.C. Rodrigues, A. Bleuzé