SageManifolds: differential geometry with SageMath

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Contraintes d'Einstein : passé, présent et futur

Laboratoire de Mathématiques d'Avignon, France

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Outline

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SageMath in a few words

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SageMath is based on Python

- no need to learn any specific syntax to use it
- Python is a powerful *object oriented language*, with a neat syntax
- SageMath benefits from the Python ecosystem (e.g. Jupyter notebook, NumPy, Matplotlib)

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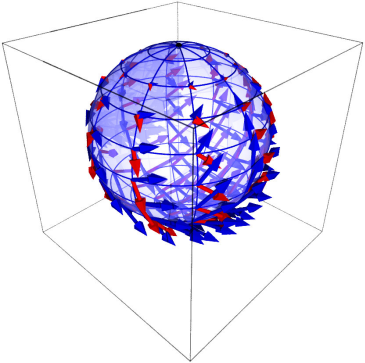
SageMath is developed by an enthusiastic community

- mostly composed of mathematicians
- welcoming newcomers

Differential geometry with SageMath

SageManifolds project: extends SageMath towards **differential geometry** and **tensor calculus**



Stereographic-coordinate frame on $\mathbb{S}^2$

- https://sagemanifolds.obspm.fr
- $\sim$ 119,000 lines of Python code
- fully included in SageMath (after review process)
- $\sim$ 30 contributors (developers and reviewers) cf. https://sagemanifolds.obspm.fr/authors.html
- dedicated mailing list
- help desk: https://ask.sagemath.org

Everybody is welcome to contribute
$\Longrightarrow$ visit https://sagemanifolds.obspm.fr/contrib.html

Current status

Already present (SageMath 10.3):

- differentiable manifolds: tangent spaces, vector frames, tensor fields, curves, pullback and pushforward operators, submanifolds
- vector bundles (tangent bundle, tensor bundles)
- standard tensor calculus (tensor product, contraction, symmetrization, etc.), even on non-parallelizable manifolds, and with all monoterm tensor symmetries taken into account
- Lie derivative along a vector field
- differential forms: exterior and interior products, exterior derivative, Hodge duality
- multivector fields: exterior and interior products, Schouten-Nijenhuis bracket
- affine connections (curvature, torsion)
- pseudo-Riemannian metrics
- computation of geodesics by numerical integration *(thanks to Karim!)*

Current status

Already present *(cont'd)*:

- some plotting capabilities (charts, points, curves, vector fields)
- parallelization (on tensor components) of CPU demanding computations
- extrinsic geometry of pseudo-Riemannian submanifolds
- series expansions of tensor fields
- symplectic manifolds
- 2 symbolic backends: Pynac/Maxima (SageMath's default) and SymPy

Future prospects:

- more symbolic backends (Giac, FriCAS, ...)
- more graphical outputs
- spinors, integrals on submanifolds, variational calculus, etc.
- connection with numerical relativity: use SageMath to explore numerically-generated spacetimes

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Vector fields on a smooth manifold

The set $\mathfrak{X}(M)$ of vector fields on a smooth manifold M over $\mathbb{K} = \mathbb{R}$ or $\mathbb{K} = \mathbb{C}$ is endowed with two algebraic structures:

1. $\mathfrak{X}(M)$ is an infinite-dimensional vector space over $\mathbb{K}$, the scalar multiplication $\mathbb{K} \times \mathfrak{X}(M) \to \mathfrak{X}(M)$, $(\lambda, \boldsymbol{v}) \mapsto \lambda \boldsymbol{v}$ being defined by

$$\forall p \in M, \quad (\lambda \boldsymbol{v})|_p = \lambda \boldsymbol{v}|_p \, ,$$

2. $\mathfrak{X}(M)$ is a module over the commutative algebra $C^\infty(M)$, the scalar multiplication $C^\infty(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$, $(f, \boldsymbol{v}) \mapsto f\boldsymbol{v}$ being defined by

$$\forall p \in M, \quad (f\boldsymbol{v})|_p = f(p)\boldsymbol{v}|_p \, ,$$

   the right-hand side involving the scalar multiplication by $f(p) \in \mathbb{K}$ in the vector space T_pM.

$\mathfrak{X}(M)$ as a $C^\infty(M)$-module

$\mathfrak{X}(M)$ is a ***free module*** over $C^\infty(M) \iff \mathfrak{X}(M)$ admits a basis

If this occurs, then $\mathfrak{X}(M)$ is actually a ***free module of finite rank*** over $C^\infty(M)$ and $\mathrm{rank}\,\mathfrak{X}(M) = \dim M = n$.
One says then that M is a ***parallelizable*** manifold.
A basis $(\boldsymbol{e}_a)_{1\leq a\leq n}$ of $\mathfrak{X}(M)$ is called a ***vector frame***

Basis expansion[1]:

$$\forall \boldsymbol{v} \in \mathfrak{X}(M), \quad \boldsymbol{v} = v^a \boldsymbol{e}_a, \quad \text{with } v^a \in C^\infty(M) \tag{1}$$

At each point $p \in M$, (1) gives birth to an identity in the tangent space T_pM:

$$\left.\boldsymbol{v}\right|_p = v^a(p) \left.\boldsymbol{e}_a\right|_p, \quad \text{with } v^a(p) \in \mathbb{K},$$

which is nothing but the expansion of the tangent vector $\left.\boldsymbol{v}\right|_p$ on the basis $(\left.\boldsymbol{e}_a\right|_p)_{1\leq a\leq n}$ of the vector space T_pM.

[1] Einstein's convention for summation on repeated indices is assumed.

Parallelizable manifolds

M is **parallelizable** $\iff$ $\mathfrak{X}(M)$ is a free $C^\infty(M)$-module of rank n
$\iff$ M admits a global vector frame
$\iff$ the tangent bundle is trivial: $TM \simeq M \times \mathbb{K}^n$

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Examples of parallelizable manifolds

- $\mathbb{R}^n$ (global coordinate chart $\Rightarrow$ global vector frame)
- the circle $\mathbb{S}^1$ (*rem:* no global coordinate chart)
- the torus $\mathbb{T}^2 = \mathbb{S}^1 \times \mathbb{S}^1$
- the 3-sphere $\mathbb{S}^3 \simeq \mathrm{SU}(2)$, as any Lie group
- the 7-sphere $\mathbb{S}^7$
- any orientable 3-manifold (Steenrod theorem)

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Examples of non-parallelizable manifolds

- the sphere $\mathbb{S}^2$ (hairy ball theorem!) and any n-sphere $\mathbb{S}^n$ with $n \notin \{1, 3, 7\}$
- the real projective plane $\mathbb{RP}^2$

SageMath implementation of vector fields

Choice of the $C^\infty(M)$-module point of view for $\mathfrak{X}(M)$, instead of the infinite-dimensional $\mathbb{K}$-vector space one

$\Longrightarrow$ implementation advantages:

- reduction to finite-dimensional structures: free $C^\infty(U)$-modules of rank n on parallelizable open subsets $U \subset M$
- for tensor calculus on each parallelizable open set U, use of exactly the same `FiniteRankFreeModule` code as for tangent spaces

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Decomposition of M into parallelizable parts

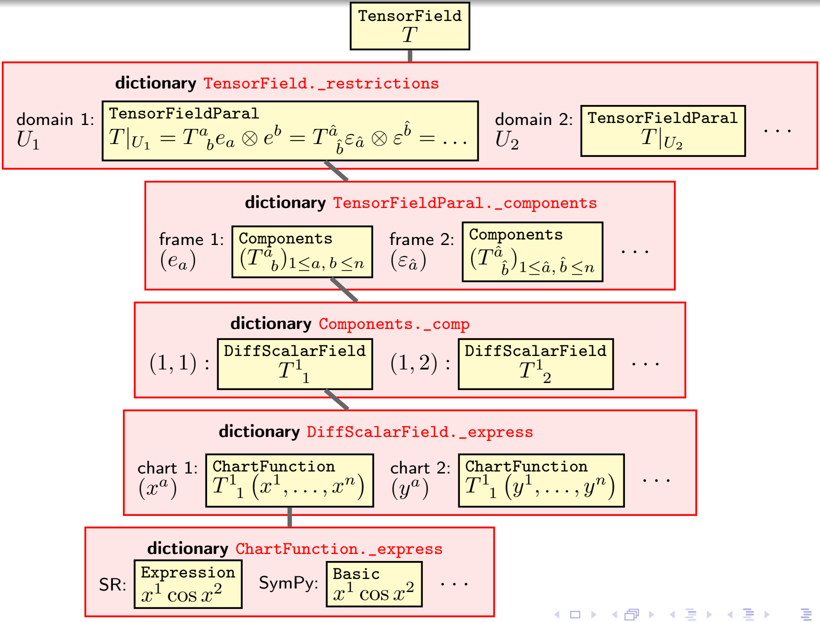
Assumption: the smooth manifold M can be covered by a finite number m of parallelizable open subsets U_i $(1 \leq i \leq m)$

Example: this holds if M is compact (finite atlas)

More details on the implementation:

[E. Gourgoulhon & M. Mancini, Les cours du CIRM **6**, 1 (2018)]

Tensor field storage



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Constraints on a Boyer-Lindquist slice of Kerr spacetime

SageMath Jupyter notebook:

https://nbviewer.org/github/sagemanifolds/SageManifolds/blob/master/Notebooks/SM_Kerr_constraints.ipynb

(In the nbviewer menu, click on to run an interactive version on a Binder server)

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Examples in Schwarzschild spacetime

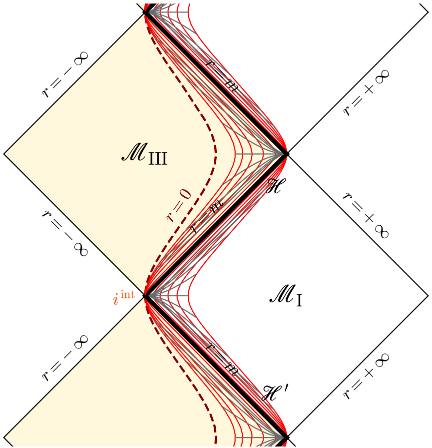
- A short demo:
  https://nbviewer.jupyter.org/github/egourgoulhon/SageMathTour/blob/master/Notebooks/demo_Schwarzschild.ipynb
- A longer example with computation of geodesics:
  https://nbviewer.org/github/egourgoulhon/SageMathTour/blob/master/Notebooks/demo_pseudo_Riemannian_Schwarzschild.ipynb
- Kruskal-Szekeres and isotropic coordinates:
  https://nbviewer.org/github/sagemanifolds/SageManifolds/blob/master/Notebooks/SM_Schwarzschild.ipynb

(In the nbviewer menu, click on to run an interactive version on a Binder server)

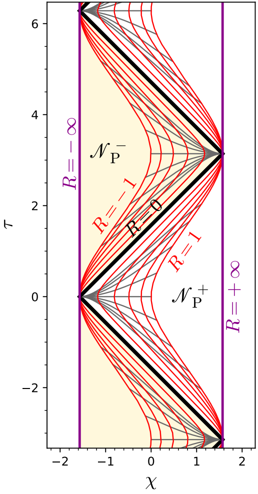
Other examples

- **Near-horizon geometry of the extremal Kerr black hole**:
  https://nbviewer.jupyter.org/github/sagemanifolds/SageManifolds/blob/master/Notebooks/SM_extremal_Kerr_near_horizon.ipynb
- **Computation of geodesics in Kerr spacetime**:
  https://nbviewer.jupyter.org/github/BlackHolePerturbationToolkit/kerrgeodesic_gw/blob/master/Notebooks/Kerr_geodesics.ipynb
- **Tolman-Oppenheimer-Volkoff equations** (derivation of TOV system and numerical integration):
  https://nbviewer.org/github/sagemanifolds/SageManifolds/blob/master/Worksheets/v1.3/SM_TOV.ipynb

Carter-Penrose diagrams generated with SageMath



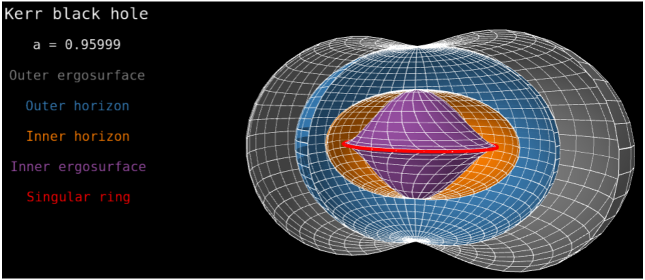
Extremal Kerr



NHEK spacetime

https://nbviewer.org/github/egourgoulhon/BHLectures/blob/master/sage/Kerr_extremal_extended.ipynb
https://nbviewer.org/github/egourgoulhon/BHLectures/blob/master/sage/NHEK_spacetime.ipynb

Animated view of horizons and ergosurfaces in Kerr spacetime



The notebook:
https://nbviewer.org/github/sagemanifolds/SageManifolds/blob/master/Notebooks/SM_Kerr_surfaces.ipynb

The animated view:
https://sagemanifolds.obspm.fr/images/animated/Kerr_surfaces.html

Image of an accretion disk surrounding a Schwarzschild BH

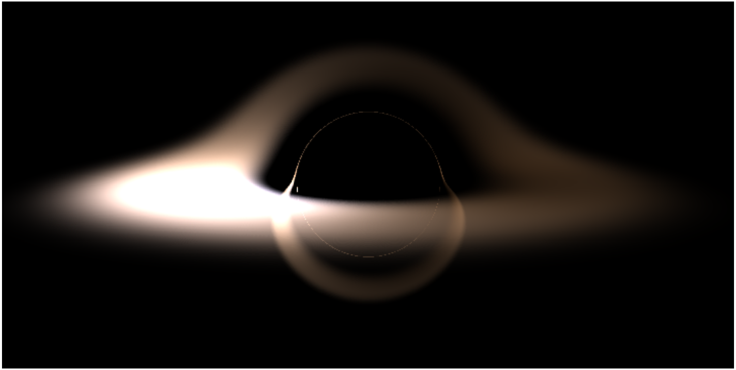


Image computed with SageMath by integrating null geodesics, cf. the notebook https://nbviewer.jupyter.org/github/sagemanifolds/SageManifolds/blob/master/Notebooks/SM_black_hole_rendering.ipynb

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Conclusions

Symbolic calculus on manifolds in the free Python-based system `SageMath`

- runs on fully specified smooth manifolds (described by an atlas)

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Many examples available at
https://sagemanifolds.obspm.fr/examples.html

Want to join the SageManifolds project or to simply stay tuned?

visit https://sagemanifolds.obspm.fr/
(download, documentation, example notebooks, mailing list)