

EinsteinPy: A Community Python Package for General Relativity

Shreyas Bapat¹, Ritwik Saha¹, Bhavya Bhatt¹, Shilpi Jain², Akshita Jain¹, Sofía Ortín Vela³, Priyanshu Khandelwal¹, Jyotirmaya Shivottam⁶, Jialin Ma⁴, Gim Seng Ng⁵, Pratyush Kerhalkar⁷, Hrishikesh Sudam Sarode¹, Rishi Sharma¹, Manvi Gupta¹, Divya Gupta¹, Tushar Tyagi¹, Tanmay Rustagi¹, Varun Singh¹, Saurabh Bansal¹, Naman Tayal¹, Abhijeet Manhas¹, Raphael Reyna⁸, Gaurav Kumar¹, Govind Dixit⁹, Ratin Kumar¹⁰, Sashank Mishra¹¹, Alpesh Jamgade¹², Raahul Singh¹³, Rohit Sanjay¹⁴, Khalid Shaikh¹⁵, Bhavam Vidyarthi¹⁴, Shamanth R Nayak K¹⁶, Vineet Gandham¹⁷, Nimesh Vashistha¹⁴, Arnav Das¹⁸, Saurabh¹⁹, Shreyas Kalvankar²⁰, Ganesh Tarone²¹, Atul Mangat²², Suyog Garg²³, Bibek Gautam²⁵, Sitara Srinivasan²⁴, Aayush Gautam²⁷, Swaastick Kumar Singh²⁶, Suyash Salampuria²⁸, Zac Yauney²⁹, Nihar Gupte³⁰, Gagan Shenoy¹⁷, and Micky Yun Chan³¹

¹ School of Computing and Electrical Engineering, Indian Institute of Technology Mandi, Mandi, Himachal Pradesh, India 175005

² Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

³ University of Zaragoza, Calle de Pedro Cerbuna, 12, 50009 Zaragoza, Spain

⁴ Georgia Institute of Technology, USA

⁵ School of Mathematics and Hamilton Mathematics Institute, Trinity College Dublin, Dublin 2, Ireland

⁶ School of Physical Sciences, National Institute of Science Education and Research, Jatni, Khurda, Odisha, India

⁷ Department of Electronics and Communication Engineering, Manipal Institute of Technology, India

⁸ California State Polytechnic University, Pomona, USA

⁹ Department of Information Technology, Indian Institute of Information Technology Lucknow, India

¹⁰ National Institute of Technology Kurukshetra, India

¹¹ Department of Information Technology, Indian Institute of Information Technology Allahabad, India

¹² Department of Mathematics, Bharath Institute of Higher Education and Research, Chennai, India

¹³ Indian Institute of Information Technology, Sri City, India

¹⁴ Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal, Karnataka, India

¹⁵ Department of Computer Engineering, Yadavrao Taskgaonkar Institute of Engineering and Technology, Mumbai University, Mumbai, Maharashtra, India

¹⁶ Department of Information and Communication Technology Engineering, Manipal Institute of Technology, Manipal, Karnataka, India

¹⁷ Department of Computer Science and Engineering, Manipal Institute of Technology, Manipal, Karnataka, India

¹⁸ Hiranandani Foundation, Powai, Mumbai, Maharashtra, India

¹⁹ Department of Physics, Dyal Singh College, University of Delhi, New Delhi, India

²⁰ K. K. Wagh Institute of Engineering Education and Research, Nashik, Maharashtra, India

²¹ Department of Computer Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India

²² Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

²³ Indian Institute of Information Technology, Design and Manufacturing, Kancheepuram, Off Vandalur-Kelambakkam Road, Melakottaiyur, Chennai, Tamil Nadu, India 600127

²⁴ Naxxatra Sciences and Collaborative Research, Bangalore, Karnataka, India

²⁵ St. Xavier's College, Maitighar, Kathmandu, Nepal

²⁶ Amity University Kolkata, West Bengal, India

²⁷ Department of Physics, Birendra Multiple Campus, Tribhuvan University, Kathmandu, Nepal

²⁸ Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

²⁹ Brigham Young University, Provo, UT 84602, United States

³⁰ Department of Physics, University of Florida, Gainesville, FL, USA

³¹ Latvia University of Life Sciences and Technologies, Lielā iela 2, Jelgava, LV-3001, Latvia

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ABSTRACT

This paper presents EinsteinPy (version 0.3), a community-developed Python package for gravitational and relativistic astrophysics. Python is a free, easy to use a high-level programming language which has seen a huge expansion in the number of its users and developers in recent years. Specifically, a lot of recent studies show that the use of Python in Astrophysics and general physics has increased exponentially. Many great frameworks came as Python packages which provide a very high level of abstraction over the dirty nitty-gritty of complex algorithms and provide an easy to use interface and pleasing user experience. One such example is Keras - a framework for deep learning which has made deep learning so easy that a person with zero programming knowledge can also train a neural network classifier. This example demonstrates the power of abstraction which is achievable in Python. The aim of the EinsteinPy is no different and is developed keeping in mind the state of a theoretical gravitational physicist with little or no background in computer programming and trying to work in the field of numerical relativity or trying to use simulations in their research. Currently, EinsteinPy supports simulation of time-like and null geodesics and calculates trajectories in different

background geometries some of which are Schwarzschild, Kerr, and KerrNewmann along with coordinate inter-conversion pipeline. It has a partially developed pipeline for plotting and visualization with dependencies on libraries like Plotly, matplotlib, etc. One of the unique features of EinsteinPy is a sufficiently developed symbolic tensor manipulation utilities which are a great tool in itself for teaching yourself tensor algebra which for many beginner students can be overwhelmingly tricky. EinsteinPy also provides few utility functions for hypersurface embedding of Schwarzschild spacetime which further will be extended to model gravitational lensing simulation. The current version of the library is in a state that can be used by any serious student of general relativity trying to get the essence of this beautiful subject but is somewhere lost in the heavy mathematical formalism of the subject. EinsteinPy provides such students to really see through the equations and visualize what's really happening.

Key words. gravitational physics – astrophysics – simulations – black holes – astropy

1. Introduction

The relativistic theory of gravity paved its way to the ground in 1916, when Prof. Albert Einstein published his paper on the general theory of relativity 1916. This elegant and rigorous framework was a generalized version of gravity-free theory - special relativity, which he published earlier in 1905. Even after almost a hundred years after Einstein wrote down the equations of General Relativity, solutions of the Einstein field equations remain extremely difficult to find beyond those which exhibit significant symmetries.

We can study the behaviour of solutions under a high degree of symmetry considerations and could even solve analytically for highly unrealistic systems. In case of problems relevant to astrophysical and gravitational physics research, it remains a big daunting question on how to get around the problem of solving these field equations. This question is so profound that it has a separate field of research which goes with the name of numerical relativity and attempts to use computation science and programming to numerically obtain solutions of the equations (which would be the background geometry) for some turbulent region where most of the interesting dynamics are happening (as we can not solve for an infinitely large grid due to restrictions imposed on us by space and time complexity and computation power).

The field of numerical relativity is growing rampantly with the vast literature on algorithms, numerical methods and theoretical formulations (from basic 3+1 decomposition formulation to more sophisticated ones) with the development of robust and involved frameworks that provide a complete programming ecosystem and have proved to be essential tools for any numerical relativity researcher.

Reflecting the other end of the research community stands the major section of theoretical physicists which counts the majority as a novice in programming. The head challenge is the fact that the usage of these frameworks demands heavy use of high-level programming languages like C, C++, Python, etc. Though Python provides a vast room for abstractions, no library existed that focused towards numerical relativity, eventually, the need of python library dedicated to general relativity became the propellant for the team and thus they made dauntless efforts to cover the space for this Python library. Since then, EinsteinPy has seen a lot of contributions from people all over the world and many "good to go" functionalities are already provided in this and previous versions.

EinsteinPy is made to provide a set of tools which can make numerical computations for solving Einstein's field equations an easy job for anyone who does not want to deal with intricacies of the subject along with few, very basic but powerful functionalities that could be used by anyone who wants to learn the subject of general relativity with every minute detail.

The library is as an attempt to provide programming and numerical environment for numerous numerical relativity problems like geodesics plotter, gravitational lensing and ray tracing, solving and simulating relativistic hydrodynamical equations, plotting of black hole event horizons, solving Einstein's field equations and simulating various dynamical systems like binary merger etc.

EinsteinPy provides an open-source and open-development core package and aims to build an ecosystem of affiliated packages that support numeric relativity functionality in the Python programming language. EinsteinPy core package is now a feature-rich library of sufficiently general tools and classes that support the development of more specialized code.

In the further coming section, we discuss with some of the features of the current as well previous version and the plans which are yet to be implemented in the upcoming versions. Also, we describe a few code snippets to explain the usage of the library on which more details can be found on the project website. We start this paper by describing the way EinsteinPy functions followed by the main software efforts developed by the EinsteinPy itself with proper detailed documentation of the current version release. We end with a short vision for the future of EinsteinPy to its contribution in the field of computational methodology in gravitational and relativistic Astrophysics.

2. Data Types

The EinsteinPy package provides some core data types for calculating, operating, visualizing geodesics and black holes. There are some data types created for symbolic manipulations and calculations of relativistic tensors. The most important data types for EinsteinPy are Body, Geodesic and BaseRelativityTensor objects that support defining and creating new bodies, storing and calculating geodesic for bodies, and handling respectively. The main purpose of these core classes is to standardize the way calculations and visualizations are done for various kinds of heavy cosmic bodies and black holes. The classes always maintain the consistency in units of measurement wherever applicable, and create a consistent and clean API for any non-programmer to understand. The classes are designed such that it resembles the flow of physics and are as intuitional as possible. These core classes also include a rigid architecture for data manipulation and visualizations wherever applicable. Following sections provide deep insight into the above mentioned three core data types of EinsteinPy:

2.1. Body

The Body data type helps define an attractor i.e. the central black-hole or the heavy mass object and later the objects under its influence. The bodies can have their characteristics defined then and there thus helping the user create the system easily.

2.2. Geodesic

A geodesic is the path that an-accelerating particle would follow. In the plane, the geodesics are straight lines. On the sphere, the geodesics are great circles. The Geodesic data type helps define the geodesic of a body in the presence of an attractor or more aptly, according to the system user created. These Geodesic objects can be defined for any configuration and metric.

2.3. BaseRelativityTensor

This is a base class from which other tensors in *symbolic* module are derived. The user can use this class to create his/her own tensor while using the various in-built functions provided by this class. The class also maintains the indicial configuration of the tensor (contravariant and covariant indices), calculates the free variables used in describing the tensor other than those which depicts the axis of space-time itself (e.g. t, x, y, z). The class has a function to convert the symbolic tensorial quantities into functions where actual numerical values can be substituted.

3. Unit Handling

All user-facing functionality provided by EinsteinPy make use of Astropy Astropy Collaboration et al. (2013) units. All functions and objects must have their input constrained to the appropriate type of unit (e.g., length, mass or energy). Inputs can then be provided with any units that match the required type (e.g., millimeters and inches are both valid units for length) and conversions occur automatically without user intervention. The `einsteinpy.constant` subpackage contains a few standard constants.

4. Development Model

The EinsteinPy Project follows an open development model, which is widely used in the scientific Python community and other computational astrophysics packages. The project is hosted on GitHub as a public repository with restricted write access to some key people. However, anyone is welcomed and is encouraged to make code contributions and suggest changes using pull requests. Since the repository containing the codebase is licensed under an open and permissive MIT licence, the project allows commercial use, modification, sub licensing, distribution and private use as long as the copyright notice and license are redistributed. The project uses git for distributed version control and relies on CircleCI, Codefactor, GitHub Actions etc. for running the unit tests and other CI checks for every pull request. The code quality is maintained at the highest standards with a strong control on the cyclomatic complexity, code linting, imports ordering and a proper docstring wherever necessary. Every contribution is reviewed to further see if it fulfils the following requirements:

- The code must strictly adhere to the PEP8 Standards, on the top of it, the code must be lined with black to save the reviewer's time identifying the changes made and reduce the diff generated because of the patch.
- The imports in the code must be sorted using tools such as isort.
- The documentation follows numpy like docstrings, and a proper reStructured Text syntax is followed for writing the documentation.
- The changelog is populated at release-time by the lead developer and the releasing developer

EinsteinPy further follows a trunk-based development model, which ensures a new branch for every minor release and new patch release made using the minor release branch. All the latest changes are kept on the master branch on GitHub and the relevant issues are closed as soon as the pull request solving it merges onto the master. A release having the changes is made at a later date. EinsteinPy only supports the latest bleeding-edge Python, Numpy (Van der Walt et al. 2011) and Astropy (Virtanen et al. 2019) astropy:2018 versions. All the stable Python versions after Python 3.5 are supported. All the code snippets written follow the guidelines of numba (Lam et al. 2015) to accelerate the Python code and make the simulations faster.

5. The EinsteinPy Core Package

This section explains in detail, the modules available within EinsteinPy core package, their API and the purpose they serve.

5.1. Metric

This module captures all the geometric and causal structure of specific space-times, and can calculate trajectories in a given space-time. The module derives its name from Metric Tensor, a tensorial quantity used to describe differential lengths, especially in curved space-time. However, this module serves more than its usual definition and ultimately leads us to obtain geodesics of particles in a space-time with high curvature, where notions of Newtonian physics fail.

5.1.1. Schwarzschild Metric

Karl Schwarzschild pioneered the analysis of the relation between the size of black hole and its mass and this work paved the way for the first exact solution of Einstein's Field Equation under the limited case of single spherical non-rotating, non-charged body. The metric equation (Schwarzschild 1916) corresponding to a space-time centred around a body in the above described conditions is given by,

$$ds^2 = -c^2 d\tau^2 = -(1 - \frac{r_s}{r})c^2 dt^2 + \frac{1}{(1 - \frac{r_s}{r})} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \quad (1)$$

Schwarzschild Radius is a limit below which the degree of space-time curvature causes the particle to undergo irreversible gravitational collapse wherein the particle would need a speed greater than speed of light to escape singularity.

As $r \rightarrow \infty$, the metric defined above starts to approximate flat Minkowski space-time, thus showing that Schwarzschild geometry is asymptotically flat.

If supplied with initial position and velocity of a particle with negligible mass (in comparison to the central body), we can obtain the geodesics of the particle for a given range of proper time τ , as it boils down to a set of eight differential equations numerically solvable by a class of Runge-Kutta methods.

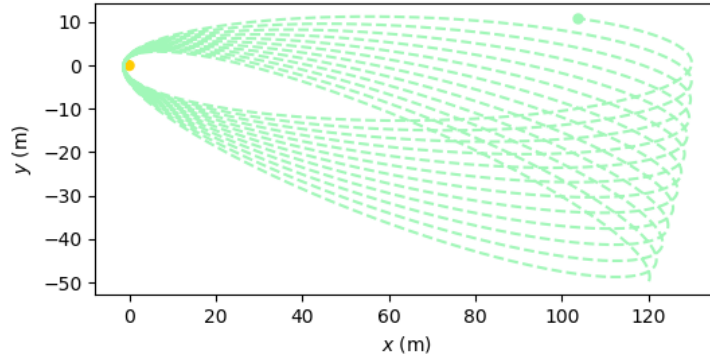


Fig. 1. Plot obtained from the above code showing the phenomenon of perihelion advance

We observe the phenomenon of perihelion advance of a particle around a heavy body due to spacetime curvature. The orbit would have been purely elliptical if plotted in accordance with Newtonian Mechanics, however, the curvature of space-time around the heavy mass shifts the orbit with each revolution. In practicality, this phenomenon is not so pronounced as no particle approaches a heavy mass this closely. For instance, Mercury advances its perihelion at a rate of 42.98 ± 0.04 arcsec/century.

5.1.2. Kerr Metric

Kerr metric (Kerr 1963) is a further generalization of Schwarzschild metric and a specific case of Kerr-Newman geometry. A space-time is defined as a "Kerr" space-time as and when the massive central body possesses an angular momentum. The corresponding metric equation which defines the space-time is,

$$g_{\mu\nu} = \begin{bmatrix} -(1 - \frac{r_s r}{\Sigma})c^2 & 0 & 0 & -\frac{r_s r a \sin^2 \theta}{\Sigma} c \\ 0 & \frac{\Sigma}{\Delta} & 0 & 0 \\ 0 & 0 & \Sigma & 0 \\ -\frac{r_s r a \sin^2 \theta}{\Sigma} c & 0 & 0 & (r^2 + a^2 + \frac{r_s r a^2}{\Sigma} \sin^2 \theta) \sin^2 \theta \end{bmatrix} \quad (2)$$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (3)$$

where,

$$a = \frac{J}{Mc},$$

$$\Sigma = r^2 + a^2 \cos^2 \theta,$$

$$\Delta = r^2 - r_s r + a^2$$

J is the angular momentum of the body and all the other symbols hold their usual meanings as discussed in ???. The coordinate system used to describe the metric is Boyer-Lindquist coordinate system.

APIs for *Schwarzschild*, *Kerr* and *KerrNewman* are consistent and code structure remains same for the sake for clarity and intuitiveness. For example,

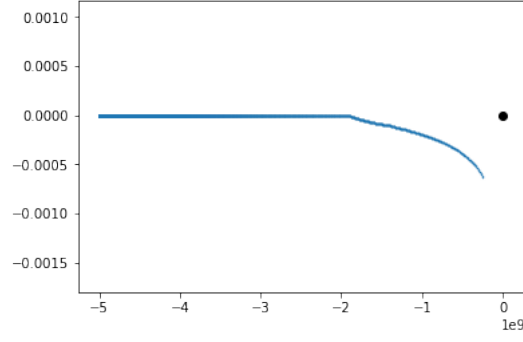


Fig. 2. Plot obtained from the above geodesics showing the phenomenon of frame dragging

5.1.3. Kerr-Newman Metric

Kerr-Newman metric (Adamo & Newman 2014) presents the most general case within single-body vacuum solutions of Einstein Field Equation. It generalizes all the quantities used to describe a black hole, as affirmed by "no hair" theorem, i.e. Charge Q , Angular Momentum J and Mass M . The metric equation is given by,

$$-ds^2 = c^2 d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (cdt - a\sin^2\theta d\phi)^2 \frac{\Delta}{\rho^2} - ((r^2 + a^2)d\phi - acdt)^2 \frac{\sin^2\theta}{\rho^2} \quad (4)$$

where,

$$a = \frac{J}{Mc},$$

$$\Sigma = r^2 + a^2 \cos^2\theta,$$

$$\Delta = r^2 - r_s r + a^2 + r_Q^2,$$

$$r_Q^2 = \frac{Q^2 G}{4\pi\epsilon_0 c^4}$$

All the other symbols convey their usual meanings, as discussed in the previous two sections Schwarzschild and Kerr Metric. For the sake of brevity, we would not go into the specifics of this class as the classes within *Metric* module share very similar APIs as inferred in section for *Kerr*.

5.2. Coordinates

The coordinates subpackage provides support for representing and transforming coordinates. EinsteinPy provides support in Cartesian, Spherical and Boyer-Lindquist Coordinate systems. All of these are inter-convertible and can be used anytime. All the calculations within the module are majorly done in Spherical system. Numba (Lam et al. 2015) is used to speed up the coordinate conversions for an extra performance boost.

EinsteinPy is the only actively maintained Python project which supports Boyer-Lindquist Coordinate system (Boyer & Lindquist 1967). Boyer and Lindquist wanted to modify the Kerr metric in a form closer to the usual form of the Schwarzschild metric. To do this, they defined a new coordinate system(t, r, θ, ϕ). In spherical coordinates where surfaces of constant r are spheres, but in Boyer-Lindquist coordinates the corresponding surfaces are ellipsoids.

5.3. Symbolic

General Relativity required heavy mathematical formulation to derive and describe various tensors attributing to various features essential for the cogent description of an arbitrary space-time. We would describe the various quantities currently supported by this module while maintaining brevity. Each quantity has its class, even scalars, which are treated as 0th order tensors.

All the mathematical quantities build upon *BaseRelativityTensor* as derived classes, which is discussed in detail in section describing *BaseRelativityTensor*.

5.3.1. MetricTensor

Metric Tensor describes the differential length elements required to measure distance in a curved(also applies to flat) space-time. It is a second order tensor and is fundamental to describe any space-time geometry. The *MetricTensor* class, being inherited from *BaseRelativityTensor*, inherits all its functions and also have some functions and constraints of its own. For example, metric tensor is bound to be a second order tensor.

Also, the library maintains an ever expanding predefined metrics for direct use in research.

5.3.2. ChristoffelSymbols

Although Christoffel Symbols belong to class of pseudo-tensors, it is inherited from *BaseRelativityTensor* to maintain homogeneity within the module. Being inherited from *BaseRelativityTensor*, it already supports the functions of its parent class and imposes some restrictions of its own, such as order of the tensor should be 3.

5.3.3. RiemannCurvatureTensor

This quantity is the most extensive measure of curvature of a space-time. It is inherited from *BaseRelativityTensor* and supports all the functions of its parent class.

5.3.4. RicciTensor

This tensor is used in solving Einstein's equation and is basically contraction of Riemann Curvature Tensor. It is inherited from *BaseRelativityTensor* and supports all the functions of its parent class.

5.3.5. RicciScalar

It is a scalar quantity obtained by contracting a given Ricci Tensor. It is inherited from *BaseRelativityTensor* and supports all the functions of its parent class. Being a scalar quantity, it does not support `change_config` unlike other tensors as discussed above.

Here is a sample code snippet, using the above discussed classes :

Listing 1. Importing Anti De-Sitter metric

```
>>> from einsteiny.symbolic.predefined import AntiDeSitter
>>> from einsteiny.symbolic import RicciTensor, RicciScalar
>>> import sympy
```

Listing 2. Obtaining Ricci Tensor from the metric

```
>>> RT = RicciTensor.from_metric(AntiDeSitter())
>>> RT.tensor()
```

$$\begin{bmatrix} 3 & 0 & 0 & 0 \\ 0 & -3 \cos^2(t) & 0 & 0 \\ 0 & 0 & (\sin^2(t) - 1) \sinh^2(\chi) - 2 \cos^2(t) \sinh^2(\chi) & 0 \\ 0 & 0 & 0 & (\sin^2(t) - 1) \sin^2(\theta) \sinh^2(\chi) - 2 \sin^2(\theta) \cos^2(t) \sinh^2(\chi) \end{bmatrix}$$

Listing 3. Deriving Ricci(Curvature) Scalar from Ricci Tensor

```
>>> RS = RicciScalar.from_ricci(RT)
>>> sympy.simplify(RS.expr) # simplifying the expression
```

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In congruence to theoretical results, the code outputs a constant negative scalar curvature for Anti De-Sitter spacetime. All the above discussed classes are called in this snippet as *RicciTensor* internally calls *RiemannCurvatureTensor*, which in turn calls *ChristoffelSymbols*.

5.3.6. Other Defined Quantities

As the library is in heavy development, new quantities are being added as and when required. Some other quantities currently supported are listed below. The quantities are all inherited from *BaseRelativityTensor*, and a similar API (same as that of discussed above) has been implemented to maintain compatibility and homogeneity. The class names denote usual quantities relevant to General Relativity.

- *EinsteinTensor*
- *StressEnergyMomentumTensor*
- *WeylTensor*
- *SchoutenTensor*

5.4. Hypersurface

This module provides basic computational functions which are essential for modelling the space-like hypersurface for any space-time geometry. Currently, the module has an implementation for Schwarzschild geometry with conversion functions from Schwarzschild coordinates to 3-D spherical coordinates and some plotting utilities. The whole module is expected to extend for providing a super-class for implementations related to gravitational lensing simulations and numerical calculations of null geodesics on hypersurfaces and deviation angles for systems which are relevant to relativistic astrophysical problems. A small code snippet for plotting the hypersurface is as follows:

Listing 4. Schwarzschild Embedding

```
>>> surface_obj = SchwarzschildEmbedding(5.927e23 * u.kg)
>>> surface = HypersurfacePlotter(embedding=surface_obj, plot_type='surface')
>>> surface.plot()
>>> surface.show()
```

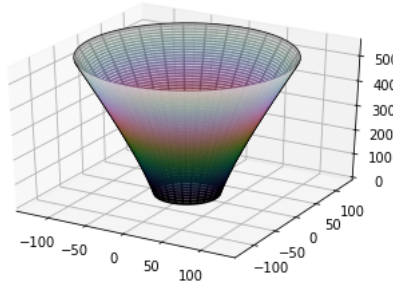


Fig. 3. Schwarzschild embedding

5.5. Plotting

The plotting ecosystem in EinsteinPy has two back-ends for two type of users. A static, matplotlib based plotter for publication-quality plots and an interactive plotly based plotter for analysis and interpretation.

The plotting module is specifically designed keeping in mind the variety of IDEs and tools people working with Python use, for example, python scripts, jupyter notebooks, spyder, pycharm etc. As plotly plots need JavaScript to render plots, it becomes difficult for the first time user to decide which backend to use. `StaticGeodesicPlotter` and `InteractiveGeodesicPlotter` undergo an internal switching depending on the environment variables and the appropriate environment aware plot is shown to the user for better user experience and interface.

The plotting module throughout the applications follow a very consistent API.

Listing 5. Plotting Module API

```
>>> data = Plotter()
>>> data.plot()
>>> data.show()
```

5.6. Rays

The rays module of EinsteinPy tries to focus on how light behaves around heavy mass object. The major functionality this module provides is the utility functions for carrying out shadow related computations for different black hole spacetimes. The module has natural data types to efficiently store impact parameters and use them in further computations related to wavelength shifts, turning point etc. The specific assumptions about the accretion process and the emission mechanisms are in accordance with that given in (Bambi 2013). The module also provide functionalities related to intensities of blue shifted and red shifted rays above and below the critical impact parameters. For mathematical formalism of the above computations refer to the (Bambi 2013) and (Shaikh et al. 2018).

This module is under heave developement since past February 2020, and we expect significant contributions to this module thanks to Google Summer of Code 2020.

6. Infrastructure

6.1. Testing

The EinsteinPy Project maintains a very high bar in accepting changes and introducing new features. Every patch of code that is accepted in the codebase through any pull request has to be well tested using some unit tests unless given an exception after

discussion with both the lead developers. Currently, the coverage of unit tests, which means the total fraction of codebase run by at least one unit test is 94% and we hope to improve it in the future. The 100% code coverage for this software at this level is not possible because of the lack of accurate data to test the code against. We deliberately leave some parts of the codebase out of the testing loop because testing those modules is not possible with the current knowledge level and expertise. However, 94% code coverage is good enough when we consider other packages in the scientific Python community who face a similar problem.

The test suite can be run manually as well as it runs in an automated fashion on every commit as well as pull request to maintain the code standards, and make it easier for contributors to understand the implications and impact of their changes. The EinsteinPy Project uses many continuous-integration services which provide services to create automated pipelines for code inspection, unit testing, coverage publishing etc. All the contributions trigger these free services (Codecov, CircleCI, Appveyor, GitHub Actions, Codefactor, Codeclimate, Hound, WIP) which are integrated with GitHub repository. All the pull requests are checked for code linting by a pep8speaks bot, which suggests the lines of code which violate the PEP8 standard to the contributor in a human-readable way. All these services run on three types of operating systems (Windows, macOS and Linux). The unit tests run on various versions of Python. They test the documentation builds, test coverage, check whether the pull request author has indicated that it is a work in progress (WIP). They also run several code linting checks which further triggers the unit test build.

6.2. Documentation and gallery

The EinsteinPy Project strives to provide high quality, up-to-date and accurate documentation of the software. The documentation is highly approachable with an easy and intuitive user interface. The documentation is self-updating with every change in the codebase and is rendered automatically from the docstrings written for each function and classes. Along with the main API, new example codes for different functionalities are added to the repository frequently in the form of jupyter notebooks. Many sections like User Guide and Developer Guide has been written for easy on-boarding of new users and contributors.

7. Community

EinsteinPy is being developed as an open-source community inside the wide and diverse general scientific python community. Our code is freely available, and we have seen a lot of people contributing and joining us since over the past year. We touched the landmark of 50 contributors recently. EinsteinPy is dedicated to problems arising in General Relativity and gravitational physics as well as encouraging open source development. EinsteinPy has benefited greatly from summer of code schemes. In 2019 EinsteinPy participated in the ESA Summer of Code In Space (SOCIS). This program is inspired by the Google Summer Of Code (GSoC) and aims to raise the awareness of open source projects related to space, promote the European Space Agency. The symbolic module in EinsteinPy project was developed during this program.

In 2020, EinsteinPy is selected as a sub-organization in Google Summer of Code under OpenAstronomy Umbrella.

8. Future

We intend to add more functionalities to our project, some of which are,

- Support for null-geodesics in different geometries, .
- Relativistic hydrodynamics
- Adaptive Mesh Refinement
- Providing numerical solutions to Einstein's equations for arbitrarily complex matter distribution.

We have an open community where we welcome suggestions from people to add functionalities/features and everyone can report bugs and issues. We wish to be as helpful as possible to people using EinsteinPy in their research.

9. Conclusions

The paper outlines the package EinsteinPy, a community and open effort for solving problems in general relativity. We discussed all the modules of the library:

- Metric Module
- Coordinates Module
- Plotting Module
- Symbolic Module
- Rays Module
- Hypersurface Module

We discuss the basic development practices that EinsteinPy follows, and the future goals.

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