Catch that asteroid with poliastro!

poliastro

Astrodynamics in Python

Juan Luis Cano - 2018-11-02 PiterPy #5 @ Crowne Plaza, Saint Petersburg

Outline

1. Introduction
2. poliastro
3. Challenges
    A. Validation
    B. Performance & API design
    C. Community building
4. How to contribute

Who am I?

* **Aerospace Engineer** with a passion for orbits 🛰
* Chair of the **Python España** non profit and co-organizer of **PyCon Spain** 🐍
* **Software Developer** at **Satellogic** 🌍
* Free Software advocate and Python enthusiast 📖
* Hard Rock lover 🎸

Follow me! [https://github.com/Juanlu001/ (https://github.com/Juanlu001/)](https://github.com/Juanlu001/)

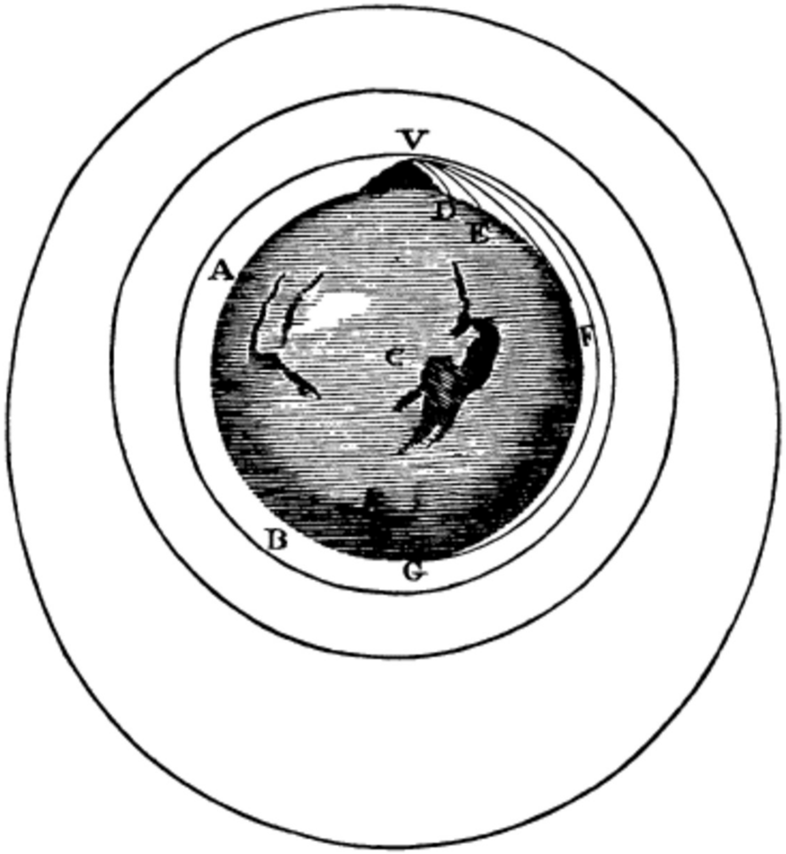
Quick intro to Orbital Mechanics

Physics → Mechanics → Celestial Mechanics → Orbital Mechanics

> *A branch of Mechanics (itself a branch of Physics) that studies practical problems regarding the motion of rockets and other human-made objects through space*

But why do bodies orbit?

The long explanation for another day :) As a summary, let's visualize this experiment imagined by Newton:



If it’s so simple, why all the fuss?

- Difficult to measure: these things move at around ~8 000 meters per second (Barcelona-Madrid in one minute) and GPS precision is not that good
- ...But great accuracy is required: we want to take pictures of specific places from 700 kilometers distance!
- Many perturbations: the Earth is not a sphere, the Moon is very close, the sunlight pushes the satellite (yes!)...
- If you lose contact with the satellite, it's a needle in a haystack

In [ ]:

```
from IPython.display import YouTubeVideo
YouTubeVideo("iEQuE5N3rwQ", width=800, height=600)
```

Introduction to poliastro

poliastro is Python library for Astrodynamics and Orbital Mechanics, focused on interactive and friendly use and with an eye on performance.

- **Pure Python**, accelerated with **numba**
- **MIT license** (permissive)
- Physical units, astronomical scales and more, thanks to Astropy
- Conversion between several orbit representations
- Analytical and numerical propagation
- Cool documentation 🚀 https://docs.poliastro.space/ (https://docs.poliastro.space/)
- Latest version 0.11.0 https://docs.poliastro.space/en/latest/changelog.html#poliastro-0-11-0-2018-09-21 (https://docs.poliastro.space/en/latest/changelog.html#poliastro-0-11-0-2018-09-21)

Brief history

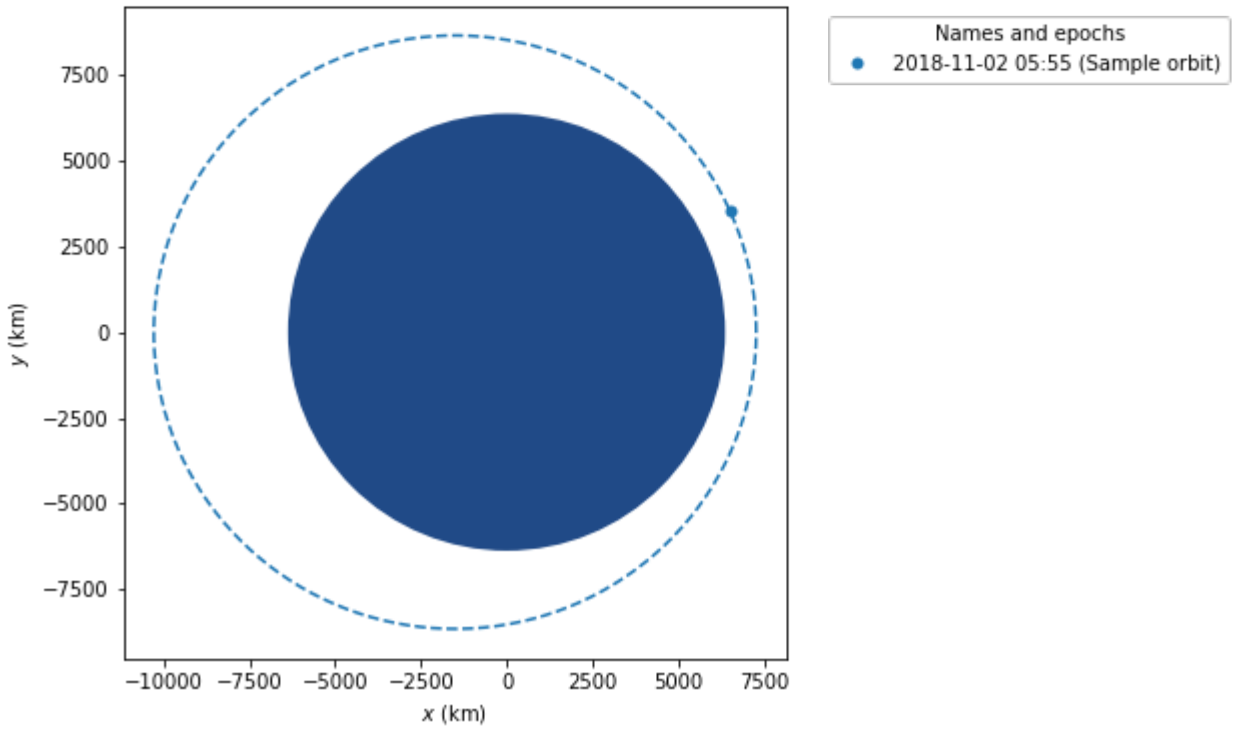
- *2013*: First version: Octave + FORTRAN + Python
- *2014*: Refactor of the API, much friendlier
- *2015*: Replace FORTRAN algorithms by Python + numba 🚀
- *2016*: Izzo algorithm (Lambert's problem), 6th ICATT @ ESA
- *2017*: Summer of Code in Space (SOCIS), OpenAstronomy & Astropy membership, 1st OSCW @ ESOC
- *2018*: Google Summer of Code (GSOC), #PyAstro18 @ Simons Fndn, expansion into the industry

Orbit plotting

In [3]:
```
r = [-6045, -3490, 2500] * u.km
v = [-3.457, 6.618, 2.533] * u.km / u.s

ss = Orbit.from_vectors(Earth, r, v, Time.now())
ss
```

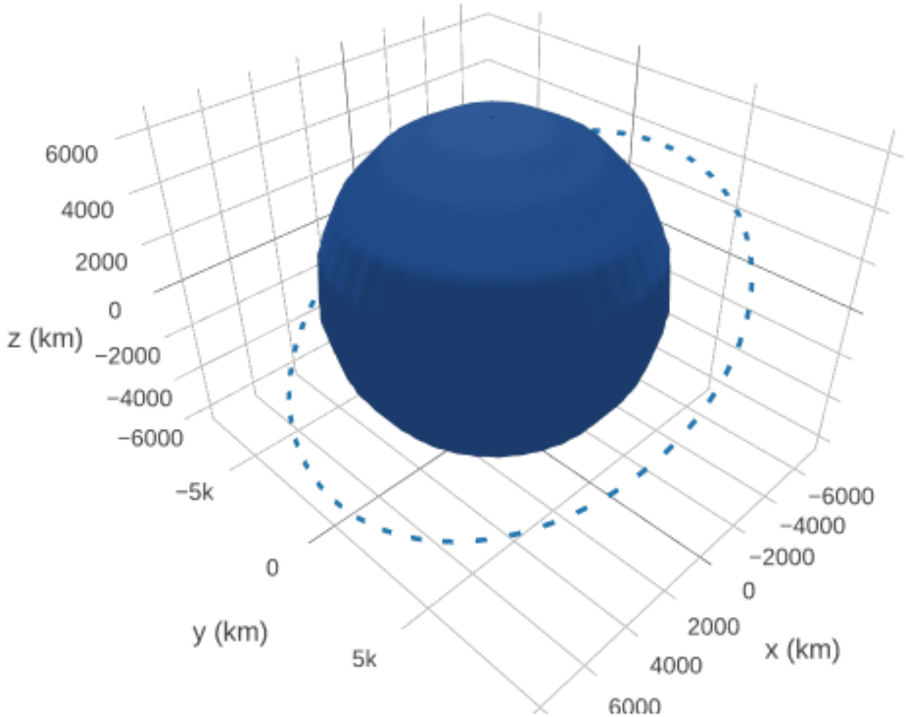
Out[3]:
```
7283 x 10293 km x 153.2 deg (GCRS) orbit around Earth (♁) at epoch 2018-11-02
05:55:57.620007 (UTC)
```

In [4]:
```
plot(ss, label="Sample orbit");
```



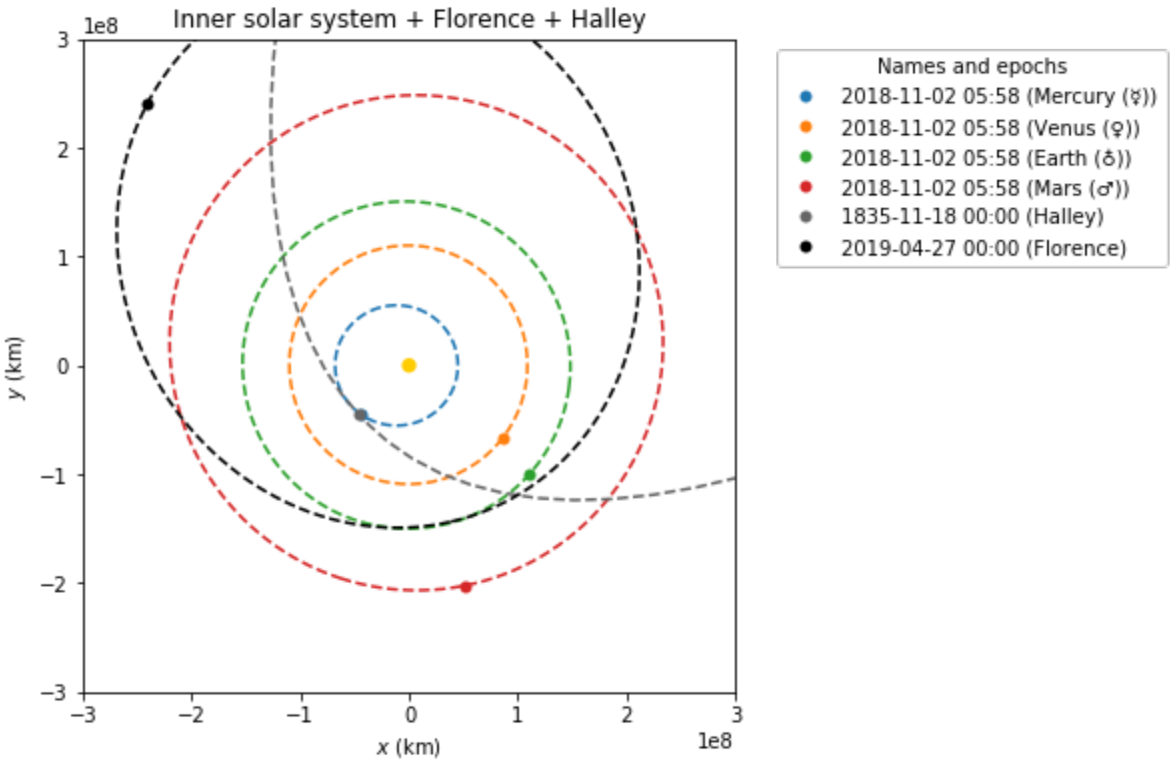
In [5]:
```
plot3d(ss, label="Sample orbit");
```

Out[5]:

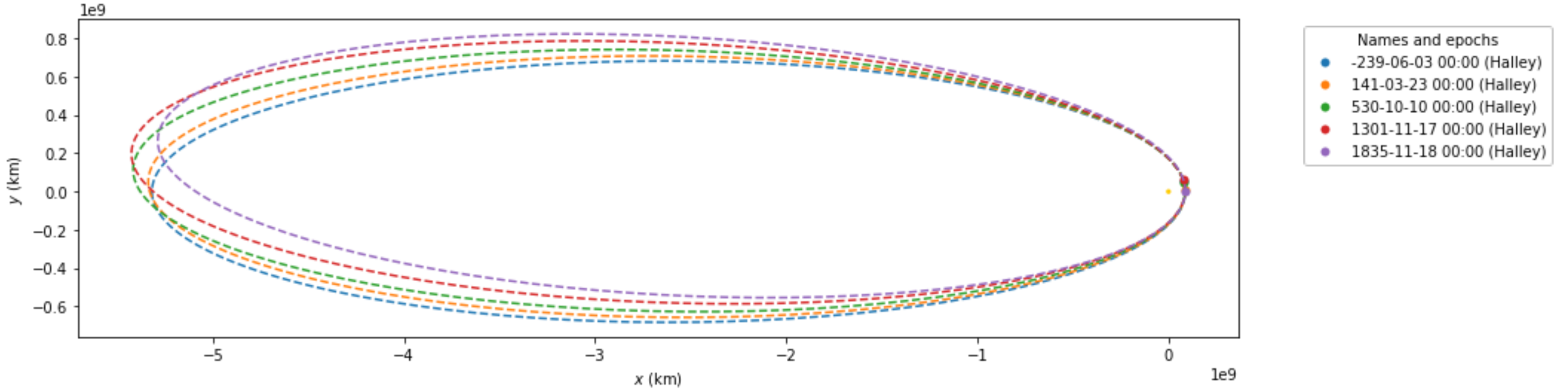


External data

In [11]:
```
frame = plot_solar_system(epoch=Time.now().tdb, outer=False)

frame.plot(halley_1835, label='Halley', color='#666666')
frame.plot(florence, label='Florence', color='#000000')

plt.title("Inner solar system + Florence + Halley")
plt.xlim(-.3e9, .3e9)
plt.ylim(-.3e9, .3e9);
```



In [13]:
```
halleys = dastcom5.orbit_from_name('1P')

frame = OrbitPlotter(num_points=200)
frame.plot(halleys[0], label='Halley')
frame.plot(halleys[5], label='Halley')
frame.plot(halleys[10], label='Halley')
frame.plot(halleys[20], label='Halley')
frame.plot(halleys[30], label='Halley');
```



Challenges

Validation

> *Unit testing a function with clear expectations is trivial. What are my expectations on numerical algorithms?*

The wroooooooooooooooong way:

In [14]:
```
def sinc(x):
    return np.sin(x) / x
```

In [15]:
```
import pytest
```

In [16]:
```
@pytest.mark.parametrize("x", [0, 1, 10])
def test_sinc(x):
    assert sinc(x) == np.sin(x) / x
```

In [17]:
```
0.1 + 0.2 == 0.3
```
Out[17]:
```
False
```
In [18]:
```
0.2 + 0.3 == 0.5
```
Out[18]:
```
True
```

A better way:

- Compare against some authoritative source: **external data or software**
- Do floating point comparisons right and **use tolerances**
- Leverage advance features such as pytest **fixtures** and automatic test generation with hypotheses [https://github.com/HypothesisWorks/hypothesis/ (https://github.com/HypothesisWorks/hypothesis/)](https://github.com/HypothesisWorks/hypothesis/)

In [19]:

```
def test_convert_from_rv_to_coe():
    # Data from Vallado, example 2.6
    attractor = Earth
    p = 11067.790 * u.km
    ecc = 0.83285 * u.one
    inc = 87.87 * u.deg
    raan = 227.89 * u.deg
    argp = 53.38 * u.deg
    nu = 92.335 * u.deg
    expected_r = [6525.344, 6861.535, 6449.125] * u.km
    expected_v = [4.902276, 5.533124, -1.975709] * u.km / u.s

    r, v = ClassicalState(attractor, p, ecc, inc, raan, argp, nu).rv()

    assert_quantity_allclose(r, expected_r, rtol=1e-5)
    assert_quantity_allclose(v, expected_v, rtol=1e-5)
```

Still some issues:

- How much precision do you ask for? Should you carry a mathematical analysis?
- What if your results don't match? Sometimes, book or paper authors respond to your comments... And sometimes don't
- The changes in precision are a result of bad data, or worse algorithms?
- How do you even track *improvements*?

External data (short summary)

- Nobody cares
- Those who care, don't share it
- Those who share, do it with 1 decimal place (true story)
- Those who share with 16 decimal places, don't describe how it was obtained (i.e. release the source)
- Those who release the source, make it impossible to compile

External software

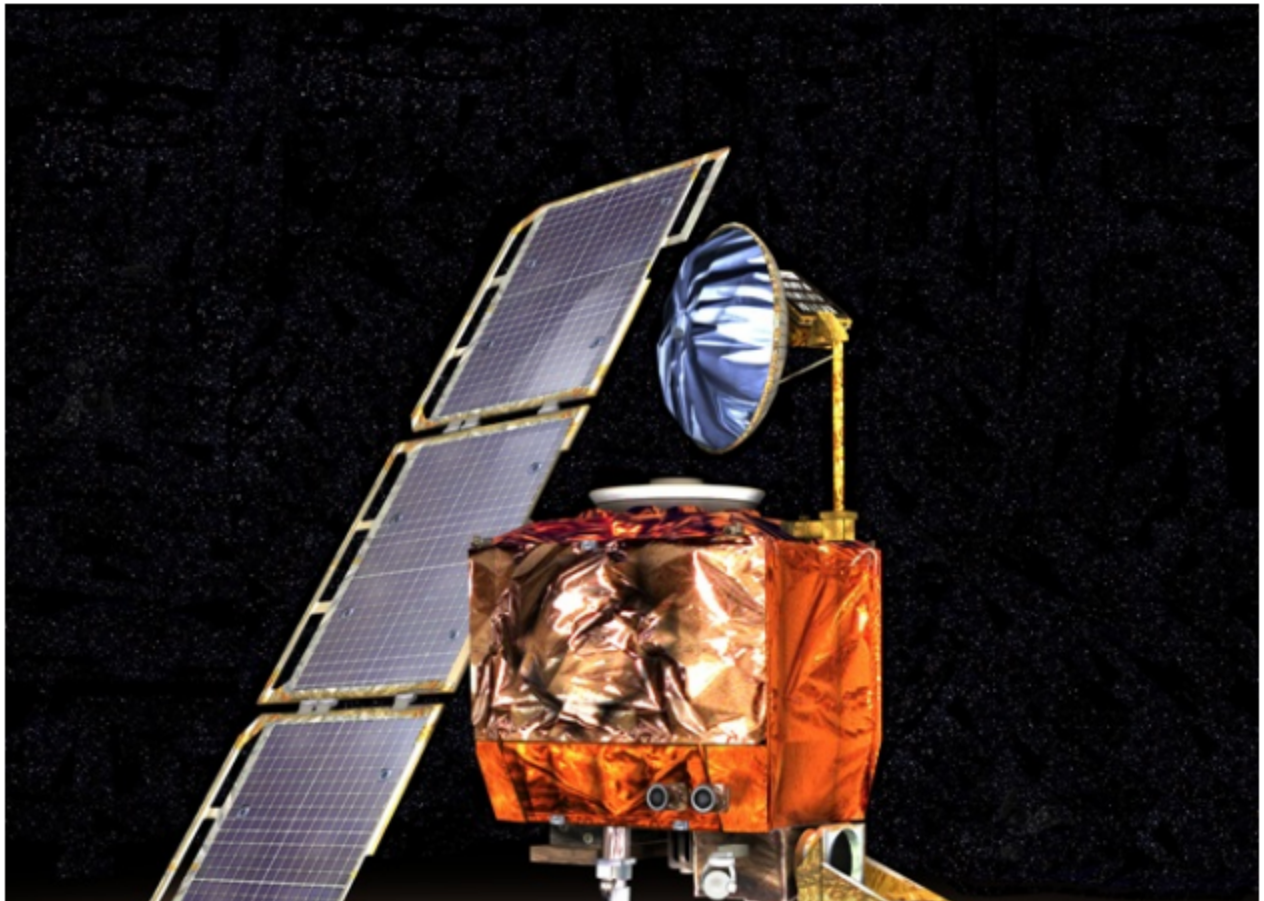
- Sometimes commercial
- Is it validated itself? (See above)
- It is often difficult to reproduce the exact setting and algorithms, most of the times because your commercial software is much more complex

...If you're really interested, go read my Final Masters Project: https://github.com/juanlu001/pfc-uc3m (https://github.com/juanlu001/pfc-uc3m)

Performance and API design

- We want to be **as user friendly as possible**
- This includes protecting the user from common mistakes
- Two annoying sources of errors: physical units and reference frames

NOV. 10, 1999: METRIC MATH MISTAKE MUFFED MARS METEOROLOGY MISSION

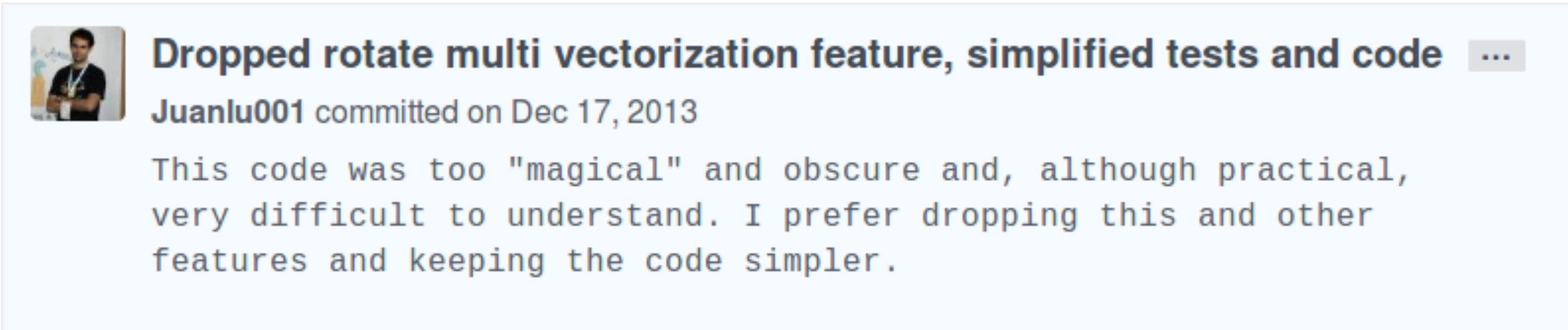


- But performance comes at a price
- *Yes, Python is slow* (compared to compiled languages)
- The places where we don't notice it is because the underlying code is compiled (e.g. NumPy)

Then, how to accelerate the code?

Vectorization

- Rewriting some code leveraging high level NumPy functions can make it way faster
- However, this works best for array manipulation - some other algorithms cannot easily be vectorized
- And even if you can, vectorized code can be impossible to read



Dropped rotate multi vectorization feature, simplified tests and code ...

Juanlu001 committed on Dec 17, 2013

```
This code was too "magical" and obscure and, although practical,
very difficult to understand. I prefer dropping this and other
features and keeping the code simpler.
```

Cython

- Mature, widely used, effective, gradual - a great project!
- Some personal problems with it:
    - I don't know any C, so it's more difficult for me
    - I wanted poliastro to be super easy to install by avoiding the "two language" problem (this includes Windows)
    - The native debugger is broken https://github.com/Juanlu001/cython-rasterio-debugging/issues/2 (https://github.com/Juanlu001/cython-rasterio-debugging/issues/2)
    - I really don't want to worry about some gore details

I don't have lots of experience with it, so I don't have solid arguments against it.

PyPy

- PyPy is a super interesting alternative Python implementation https://pypy.org/ (https://pypy.org/)
- I really really want to use it more, but there are some obstacles:
  - The documentation is a bit poor, even the changelogs
  - Lacks interest from the mainstream community (including snarky comments by Guido about "nobody using it in production")
  - Support in conda is half-broken https://github.com/conda-forge/pypy2.7-feedstock/issues/1 (https://github.com/conda-forge/pypy2.7-feedstock/issues/1)
  - PyPy has several incompatibilities with manylinux1 wheels https://bitbucket.org/pypy/pypy/issues/2617/ (https://bitbucket.org/pypy/pypy/issues/2617/)
  - manylinux2010 are almost there, but need the final push https://github.com/pypa/manylinux/issues/179 (https://github.com/pypa/manylinux/issues/179)

numba

- numba is a Python-to-LLVM JIT compiler
- When it works, it's super effective and the results are impressive!
- Debugging improved *a lot* lately
- However, its focus is numerical code: it won't accelerate high level Python features
- At the moment it's not even possible to pass a function as an argument, impeding reusability [https://github.com/numba/numba/issues/2952 (https://github.com/numba/numba/issues/2952)](https://github.com/numba/numba/issues/2952)

In [32]:
```python
def monte_carlo_pi(nsamples):
    acc = 0
    for ii in range(nsamples):
        x = random.random()
        y = random.random()
        if x ** 2 + y ** 2 < 1.0:
            acc += 1
    return 4.0 * acc / nsamples
```

In [33]:
```python
print(monte_carlo_pi(10))
print(monte_carlo_pi(1_000_000))
```

```
2.4
3.142732
```

In [34]:
```python
%timeit monte_carlo_pi(1_000_000)
```

```
390 ms ± 9.7 ms per loop (mean ± std. dev. of 7 runs, 1 loop each)
```

In [35]:
```
from numba import njit  # Forget about jit! Only nopython mode

fast_monte_carlo_pi = njit(monte_carlo_pi)
```

In [37]:
```
%timeit -n1 -r1 fast_monte_carlo_pi(1_000_000)
```

```
17.4 ms ± 0 ns per loop (mean ± std. dev. of 1 run, 1 loop each)
```

In [38]:
```
%timeit fast_monte_carlo_pi(1_000_000)
```

```
12.7 ms ± 282 µs per loop (mean ± std. dev. of 7 runs, 100 loops each)
```

In [60]:

```
%%numba_annotate
from numba import jit  # https://github.com/numba/numba/issues/2788#issuecommen
t-435288763

@jit
def monte_carlo_pi(nsamples):
    acc = 0
    for ii in range(nsamples):
        x = random.random()
        y = random.random()
        if x ** 2 + y ** 2 < 1.0:
            acc += 1
    return 4.0 * acc / nsamples

print(monte_carlo_pi(1_000_000))
```

Out[60]:

Function name: monte_carlo_pi

in file: /tmp/tmp_3pipx1l/code.py

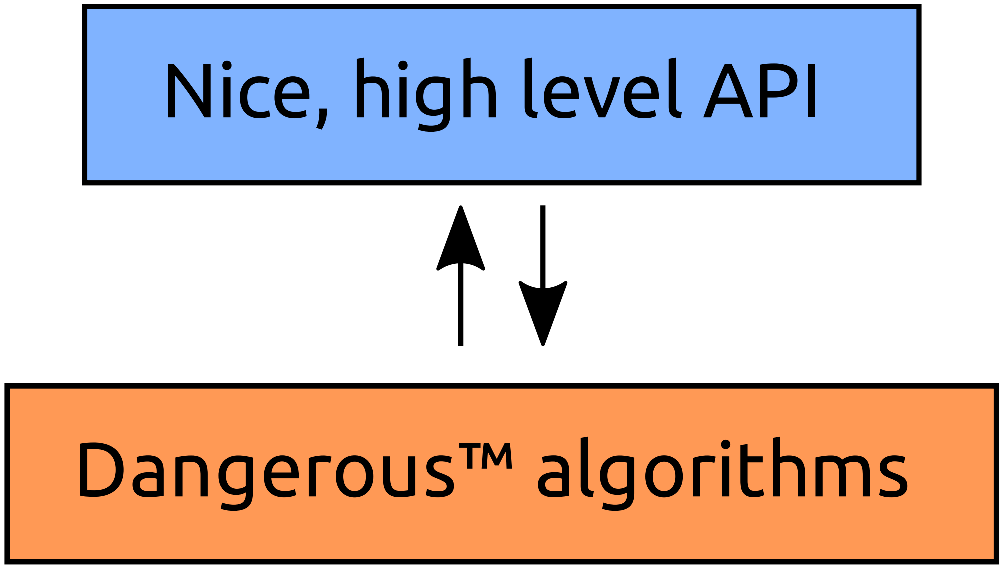
with signature: (int64,) -> pyobject

```
 3: @jit
   4: def monte_carlo_pi(nsamples):
▶ 5:     acc = 0
▶ 6:     for ii in range(nsamples):
▶ 7:         x = random.random()
▶ 8:         y = random.random()
▶ 9:         if x ** 2 + y ** 2 < 1.0:
▶ 10:            acc += 1
▶ 11:     return 4.0 * acc / nsamples
```

Solution

So... let's make our code Fortran-esque!

High level API:



- Supports mixed units and time scales, figures out the rest
- Easy to use and impossible to get wrong
- **Slow**

Dangerous™ algorithms:

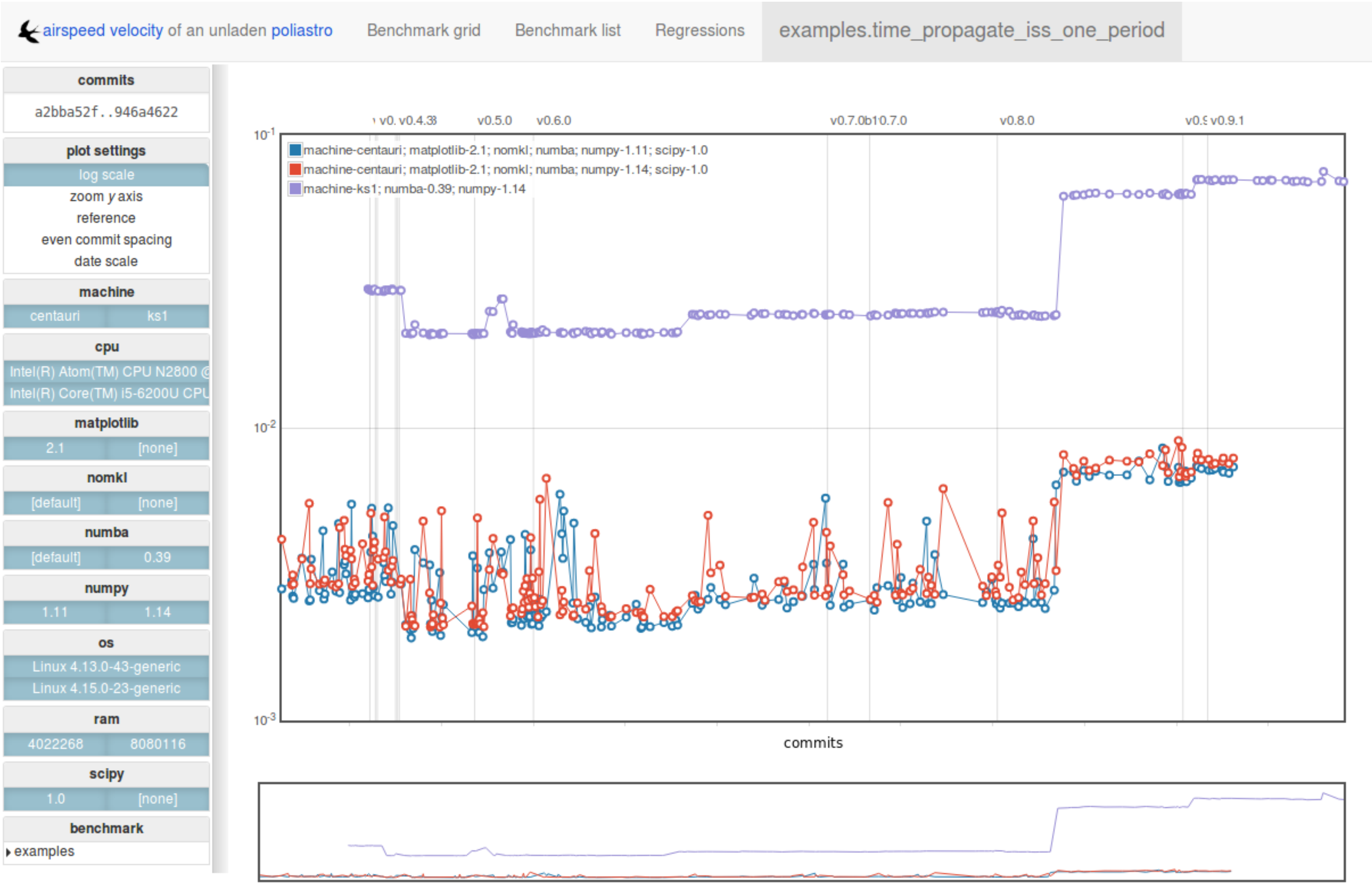
- **Fast** (easy to accelerate with numba or Cython)
- Only cares about numbers, makes assumptions on units (SI, TBD)
- **You can mess it up**

In [61]:

```python
@u.quantity_input(E=u.rad, ecc=u.one)
def E_to_nu(E, ecc):
    """True anomaly from eccentric anomaly."""
    return (E_to_nu_fast(E.to(u.rad).value, ecc.value) * u.rad).to(E.unit)
```

Measure everything!

http://poliastro.github.io/poliastro-benchmarks (http://poliastro.github.io/poliastro-benchmarks)



Community building

> *I believe the choice of license is an important one, and I advocate a BSD-style license.* ***In my experience, the most important commodity an open source project needs to succeed is users.***
>
> *-- John Hunter † [http://nipy.org/nipy/faq/johns_bsd_pitch.html (http://nipy.org/nipy/faq/johns_bsd_pitch.html)](http://nipy.org/nipy/faq/johns_bsd_pitch.html)*

- Sometimes, language wins over performance.
- Sometimes, documentation wins over features.
- Sometimes, marketing wins over quality.

Go find your users!

How to contribute?

- First and foremost: **no astrodynamics knowledge required!**
- Lots of issues with plotting, testing, internal design...
- Everything that fits de scope https://github.com/poliastro/poliastro#can-i-do-insert-awesome-thing-with-poliastro (https://github.com/poliastro/poliastro#can-i-do-insert-awesome-thing-with-poliastro) and is aligned with the vision https://github.com/poliastro/poliastro/wiki/Core-principles (https://github.com/poliastro/poliastro/wiki/Core-principles) is welcome!
- If you use the library and find bugs or outdated docs, we would love to know!
- And if you do something cool, we can publish a success story https://docs.poliastro.space/en/latest/#success-stories (https://docs.poliastro.space/en/latest/#success-stories)
- Comment on issues, join our chat, let's talk!

Per Python ad astra! 🚀

- Slides: https://github.com/poliastro/piterpy5-talk (https://github.com/poliastro/piterpy5-talk)
- poliastro chat: https://riot.im/app/#/room/#poliastro:matrix.org (https://riot.im/app/#/room/#poliastro:matrix.org)
- Twitter: https://twitter.com/poliastro_py (https://twitter.com/poliastro_py)

большое спасибо!