Extracting flow information from sparse Lagrangian trajectories

Jean-Luc Thiffeault[1] Michael Allshouse[2]

[1]Department of Mathematics
University of Wisconsin – Madison

[2]Department of Mechanical Engineering
MIT

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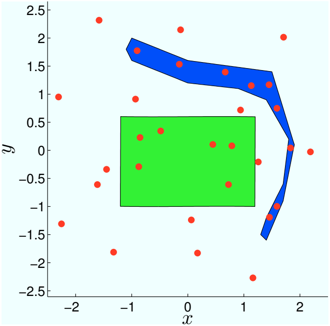
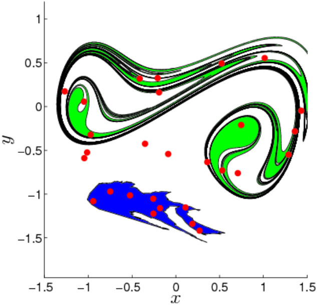
Sparse trajectories and material loops



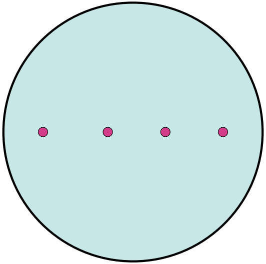


How do we efficiently detect trajectories that 'bunch' together?

[movie 1]

Mathematical background: Punctured disks

Low-dimensional topologists have long studied transformations of surfaces such as the punctured disk:

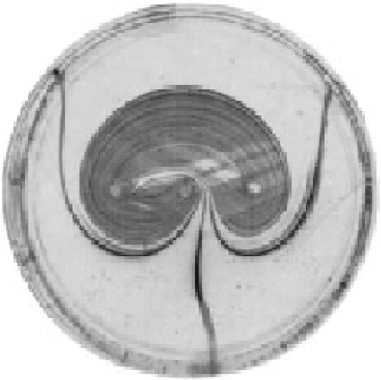


The central object of study is the homeomorphism: a continuous, invertible transformation whose inverse is also continuous.

For instance, this is a model of a two-dimensional vat of viscous fluid with stirring rods.

Punctured disks in experiments

The transformation in this case is given by the solution of a fluid equation over one period of rod motion.

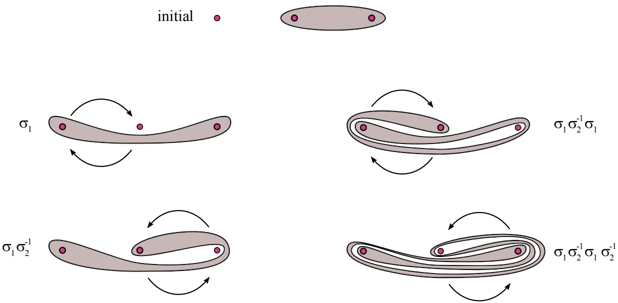


[P. L. Boyland, H. Aref, and M. A. Stremler, *J. Fluid Mech.* **403**, 277 (2000)]

[movie 2] [movie 3]

Growth of curves on a disk

On a disk with 3 punctures (rods), we can also look at the growth of curves:



We use the braid generator notation: σ_i means the clockwise interchange of the ith and $(i+1)$th rod. (Inverses are counterclockwise.)

The motion above is denoted $\sigma_1\sigma_2^{-1}$.

Growth of curves on a disk (2)

The rate of growth $h = \log \lambda$ is called the topological entropy.

But how do we find the rate of growth of curves for motions on the disk?

For 3 punctures it's easy: the entropy for $\sigma_1\sigma_2^{-1}$ is $h = \log \varphi^2$, where φ is the Golden Ratio!

For more punctures, use Moussafir iterative technique (2006).

[Thiffeault, *Phys. Rev. Lett.* (2005); *Chaos* (2010); Gouillart et al., *Phys. Rev. E* (2006) 'ghost rods']

Iterating a loop

It is well-known that the entropy can be obtained by applying the motion of the punctures to a closed curve (loop) repeatedly, and measuring the growth of the length of the loop (Bowen, 1978).

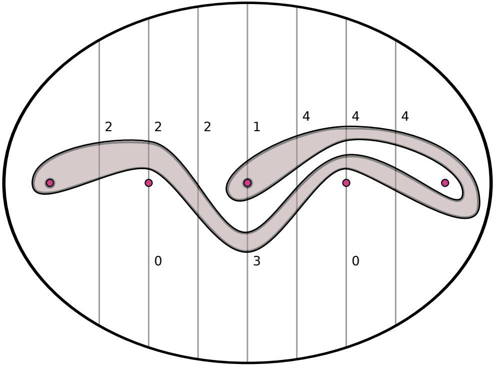
The problem is twofold:

1. Need to keep track of the loop, since its length is growing exponentially;
2. Need a simple way of transforming the loop according to the motion of the punctures.

However, simple closed curves are easy objects to manipulate in 2D. Since they cannot self-intersect, we can describe them topologically with very few numbers.

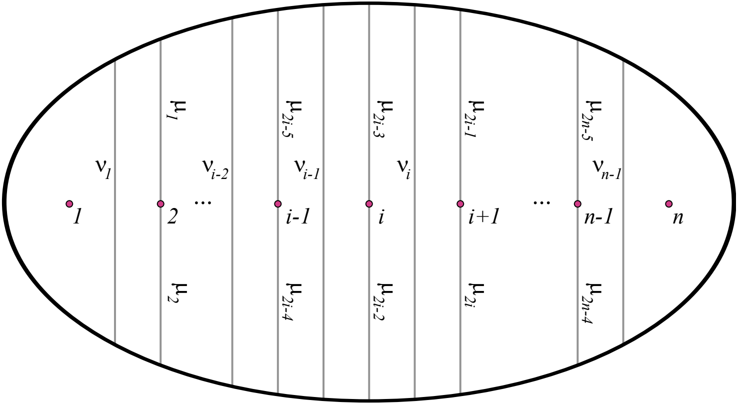
Solution to problem 1: Loop coordinates

What saves us is that a closed loop can be uniquely reconstructed from the number of intersections with a set of curves. For instance, the Dynnikov coordinates involve intersections with vertical lines:



Crossing numbers

Label the crossing numbers:



Dynnikov coordinates

Now take the difference of crossing numbers:

$$a_i = \tfrac{1}{2}\left(\mu_{2i} - \mu_{2i-1}\right), \\ b_i = \tfrac{1}{2}\left(\nu_i - \nu_{i+1}\right)$$

for $i = 1, \ldots, n-2$.

The vector of length $(2n-4)$,

$$\mathbf{u} = (a_1, \ldots, a_{n-2}, b_1, \ldots, b_{n-2})$$

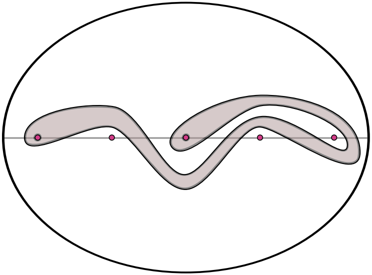
is called the Dynnikov coordinates of a loop.

There is a one-to-one correspondence between closed loops and these coordinates: you can't do it with fewer than $2n-4$ numbers.

Intersection number

A useful formula gives the minimum intersection number with the 'horizontal axis':

$$L(\mathbf{u}) = |a_1| + |a_{n-2}| + \sum_{i=1}^{n-3} |a_{i+1} - a_i| + \sum_{i=0}^{n-1} |b_i|\,,$$

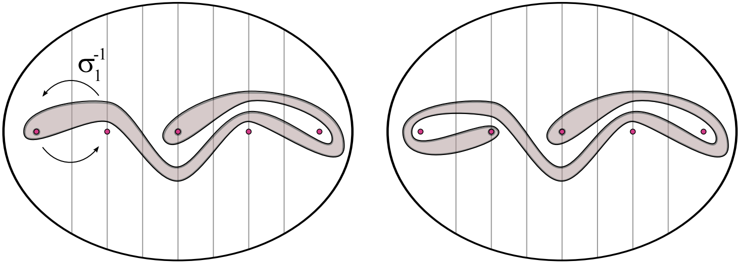


For example, the loop on the left has $L = 12$.

The crossing number grows proportionally to the the length.

Solution to problem 2: Action on coordinates

Moving the punctures according to a braid generator changes some crossing numbers:



There is an explicit formula for the change in the coordinates!

Action on loop coordinates

The update rules for σ_i acting on a loop with coordinates $(\mathbf{a}, \mathbf{b})$ can be written

$$\begin{aligned} a'_{i-1} &= a_{i-1} - b^+_{i-1} - \left(b^+_i + c_{i-1}\right)^+ , \\ b'_{i-1} &= b_i + c^-_{i-1} , \\ a'_i &= a_i - b^-_i - \left(b^-_{i-1} - c_{i-1}\right)^- , \\ b'_i &= b_{i-1} - c^-_{i-1} , \end{aligned}$$

where

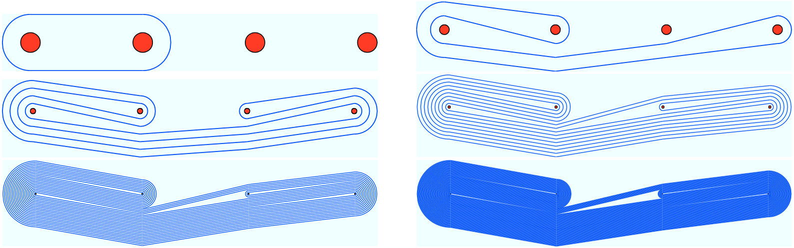
$$f^+ := \max(f, 0), \qquad f^- := \min(f, 0).$$

$$c_{i-1} := a_{i-1} - a_i - b^+_i + b^-_{i-1} .$$

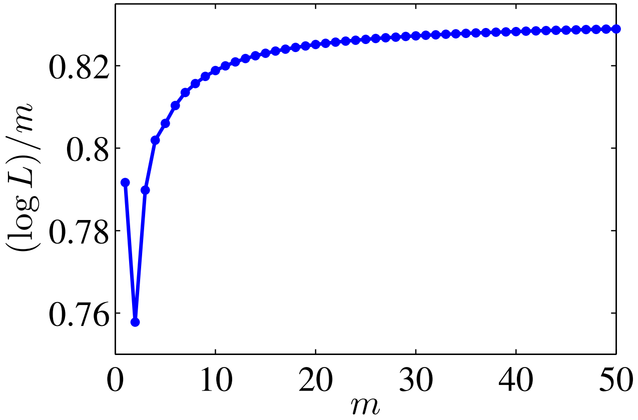
This is called a piecewise-linear action.
Easy to code up (see for example Thiffeault (2010)).

Growth of L

For a specific rod motion, say as given by the braid $\sigma_3^{-1}\sigma_2^{-1}\sigma_3^{-1}\sigma_2\sigma_1$, we can easily see the exponential growth of L and thus measure the entropy:

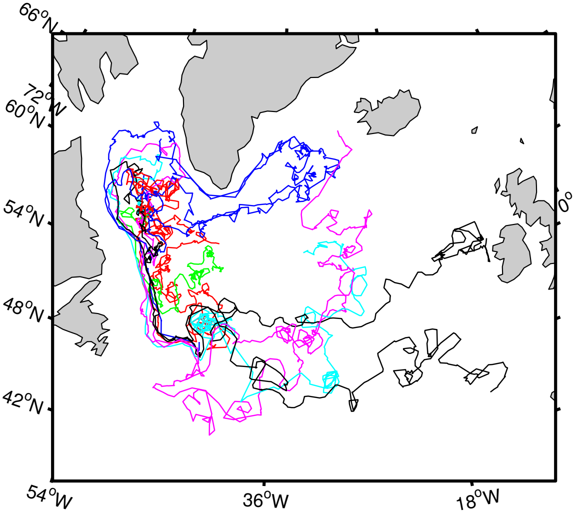


Growth of L (2)



m is the number of times the braid acted on the initial loop.

Oceanic float trajectories



Oceanic floats: Data analysis

What can we measure?

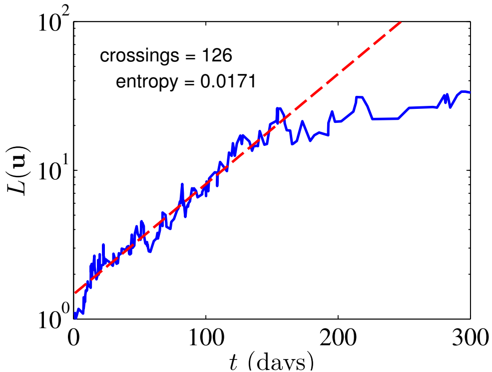
- Single-particle dispersion (not a good use of all data)
- Correlation functions (what do they mean?)
- Lyapunov exponents (some luck needed!)

Another possibility:

Compute the σ_i for the float trajectories (convert to a sequence of symbols), then look at how loops grow. Obtain a topological entropy for the motion (similar to Lyapunov exponent).

Oceanic floats: Entropy

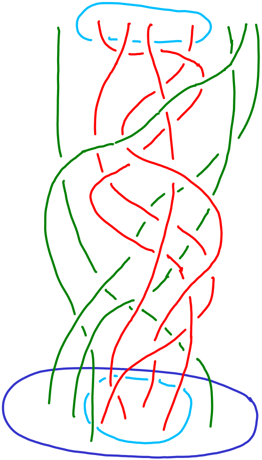
10 floats from Davis' Labrador sea data:



Floats have an entanglement time of about 50 days — timescale for horizontal stirring.

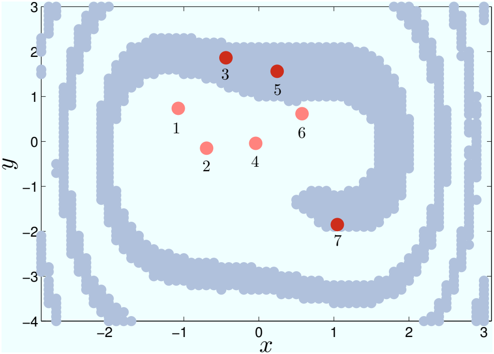
Source: WOCE subsurface float data assembly center (2004)

Lagrangian Coherent Structures



- There is a lot more information in the braid than just entropy;
- For instance: imagine there is an isolated region in the flow that does not interact with the rest, bounded by Lagrangian coherent structures (LCS);
- Identify LCS and invariant regions from particle trajectory data by searching for curves that grow slowly or not at all.
- For now: regions are not ‘leaky.’
- (See the work of Haller et al.)

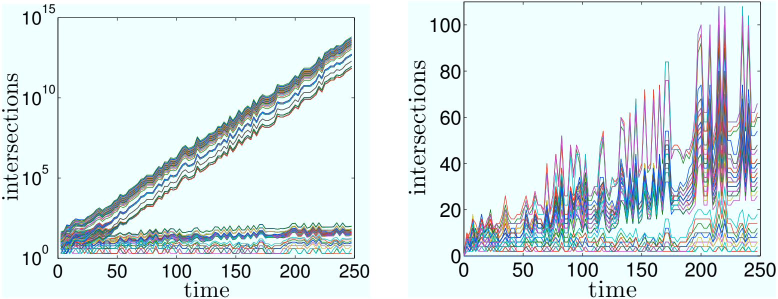
Sample system: Modified Duffing oscillator



$$\dot{x} = y + \alpha \cos \omega t,$$
$$\dot{y} = x(1 - x^2) + \gamma \cos \omega t - \delta y\,,$$

+ rotation to further hide two regions. $\alpha = .1$, $\gamma = .14$, $\delta = .08$, $\omega = 1$.

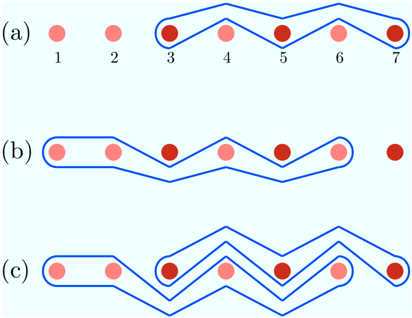
Growth of a vast number of loops

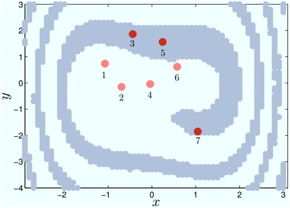


Left: semilog plot; Right: linear plot of slow-growing loops.

Clearly two types of loops!

What do the slowest-growing loops look like?





[(c) appears because the coordinates also encode ‘multiloops.’]

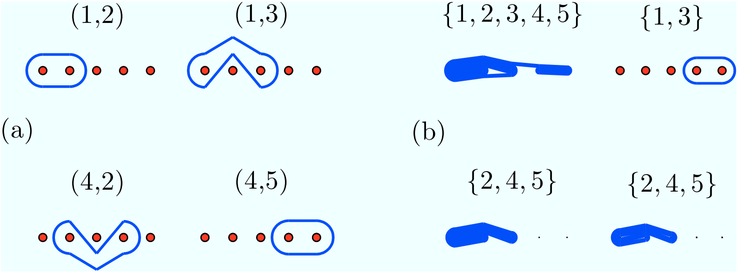
Computational complexity

Here's the bad news:

- There are an infinite number of loops to consider.
- But we don't really expect hyper-convoluted initial loops (nor do we care so much about those).
- Even if we limit ourselves to loops with Dynnikov coordinates between -1 and 1, this is still 3^{2n-4} loops.
- This is too many. . . can only treat about 10–11 trajectories using this direct method.

An improved method: Pair-loops

The biggest problem is that we only look at whether a loop grows or not. But there is a lot more information to be found in how a loop entangles the punctures as it evolves.



Consider loops that enclose two punctures at once. More involved analysis, but scales *much* better with n.

Improvement

Run times in seconds:

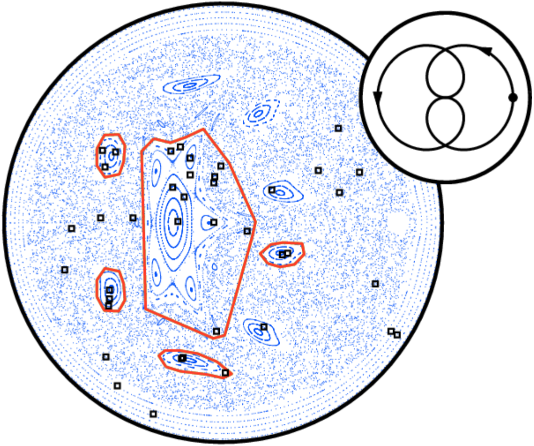
# of trajectories	6	7	8	9	10	11	20
direct method	0.46	0.70	6.0	53	462	3445	N/A
pair-loop method	9.5	11.6	12.3	13	15	20	128

Bottleneck for the pair-loop method is finding the non-growing loops. (Should scale as n^2 for large enough n.)

The downside is that the pair-loop method is much more complicated. But in the end it accomplishes the same thing.

See Allshouse & Thiffeault, *Physica D* **241**, 95–105 (2012).

A physical example: Rod stirring device



[movie 4]

Another benchmark problem: double-gyre

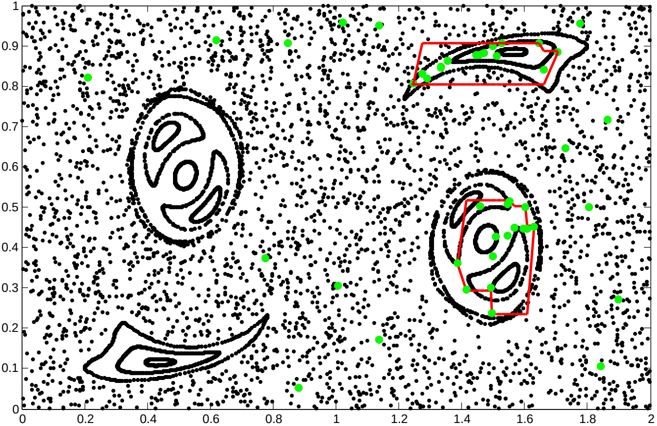
Shadden et al. (2005)

$$\dot{\mathbf{x}} = \pi A \begin{pmatrix} -\sin(\pi f(x,t))\cos(\pi y) \\ \cos(\pi f(x,t))\sin(\pi y)\,\frac{\partial f(x,t)}{\partial x} \end{pmatrix}$$

$$\begin{aligned} f(x,t) &= a(t)x^2 + b(t)x \\ a(t) &= \varepsilon\,\sin(\omega t) \\ b(t) &= 1 - 2\varepsilon\,\sin(\omega t) \end{aligned}$$

$$\varepsilon = 0.1,\ A = 0.1,\ \omega = \pi/5.$$

Double-gyre coherent structures



[movie 5]

Conclusions

- Having rods undergo ‘braiding’ motion guarantees a minimal amount of entropy (stretching of material lines);
- This idea can also be used on fluid particles to estimate entropy;
- Need a way to compute entropy fast: loop coordinates;
- There is a lot more information in this braid: extract it! (Lagrangian coherent structures);
- Is this useful? We’re still looking for a good data set to try it on! No joy so far. . .
- We’re developing Matlab tools — `braidlab`.
- Also applicable to granular media Puckett (2012).
- See Thiffeault (2005, 2010) and Allshouse & Thiffeault (2012).

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