Topological detection of Lagrangian coherent structures

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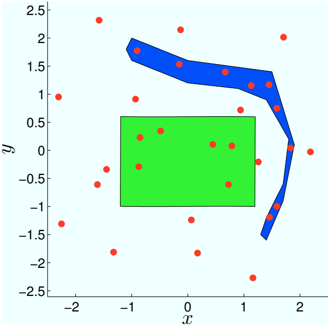
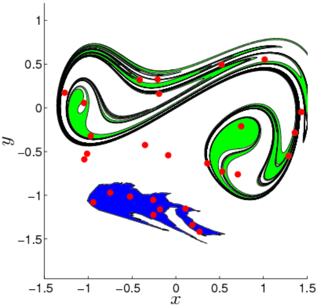
Sparse trajectories and material loops



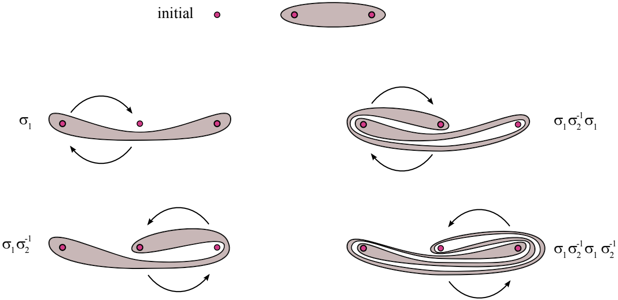


How do we efficiently detect trajectories that ‘bunch’ together?

[movie 1]

Growth of loops enclosing trajectories

For 3 trajectories, 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 trajectory. (Inverses are counterclockwise.)

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

Growth of loops (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 trajectories it's easy: the entropy for $\sigma_1\sigma_2^{-1}$ is $h = \log \varphi^2$, where φ is the Golden Ratio!

For more trajectories, 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 trajectories to a closed curve (loop) repeatedly, and measuring the growth of the length of the loop (Bowen, 1978).

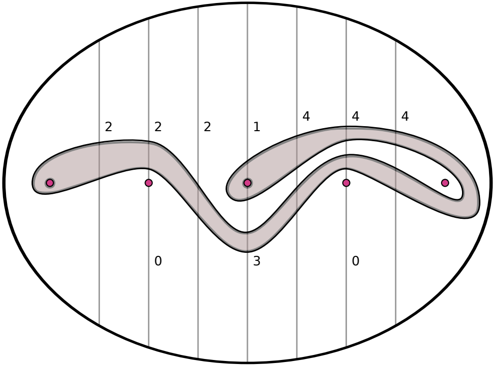
The problem is twofold:

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 trajectories.

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 crossing numbers count intersections with vertical lines:

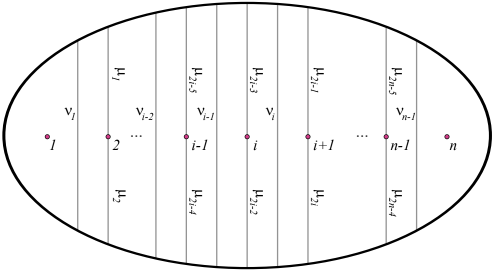


Dynnikov coordinates

Now take the difference of crossing numbers:

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

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



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

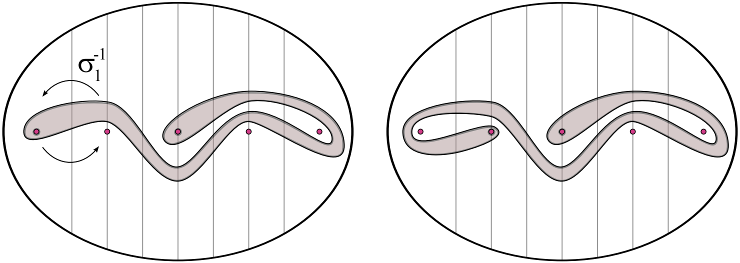
$$\mathbf{u} = (a_1, \ldots, a_{n-2}, b_1, \ldots, b_{n-2})$$

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.

Solution to problem 2: Action on coordinates

Moving the points 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

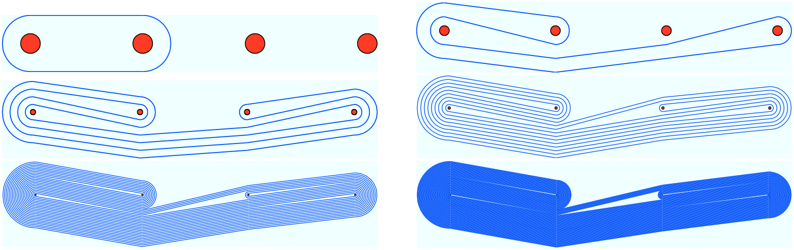
$$f^+ := \max(f, 0), \qquad f^- := \min(f, 0).$$

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

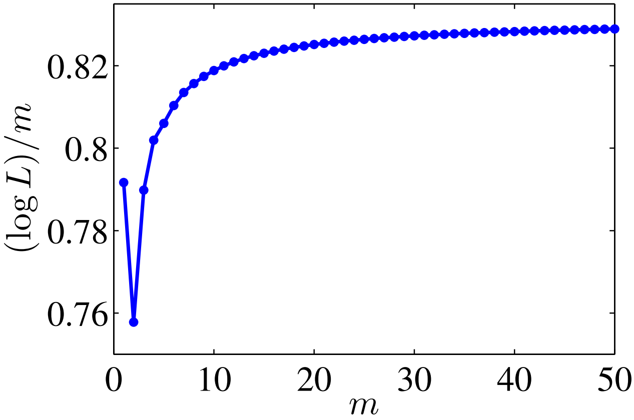
This is called a piecewise-linear action.
Easy to code up (see for example Thiffeault (2010)).

Growth of L

For a specific set of trajectories, 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:

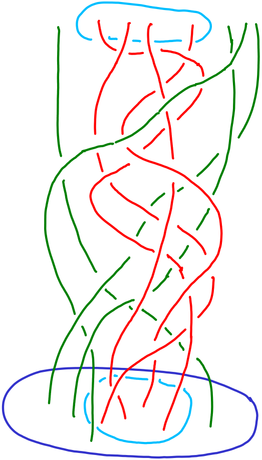


Growth of L (2)



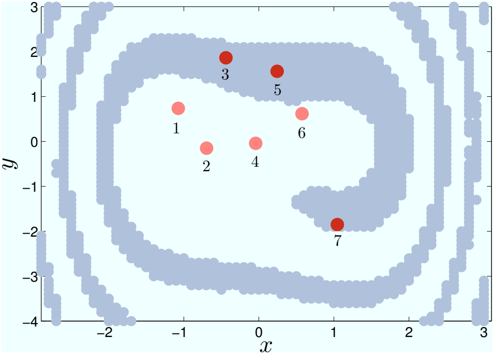
m is the number of times the braid acted on the initial loop.

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.'

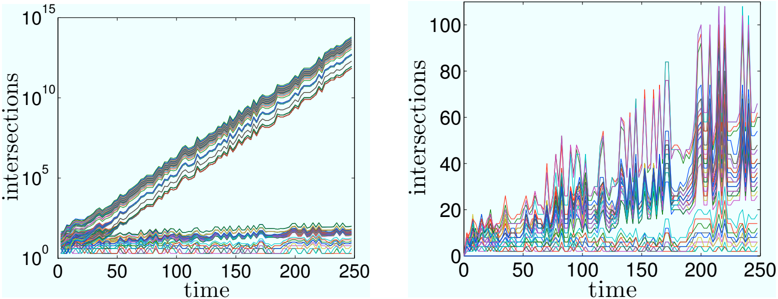
Sample system: Modified Duffing oscillator



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

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

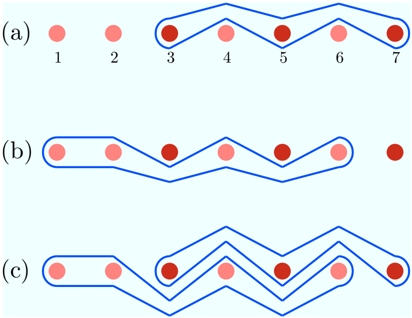
Growth of a vast number of loops

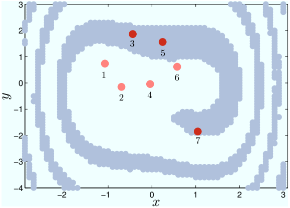


Left: semilog plot; Right: linear plot of slow-growing loops.

Clearly two types of loops!

What do the slowest-growing loops look like?





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

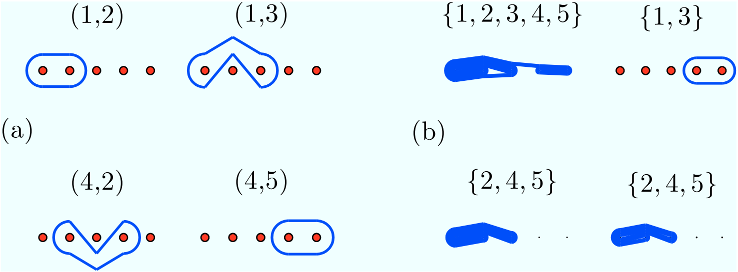
Computational complexity

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 trajectories as it evolves.



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

Improvement

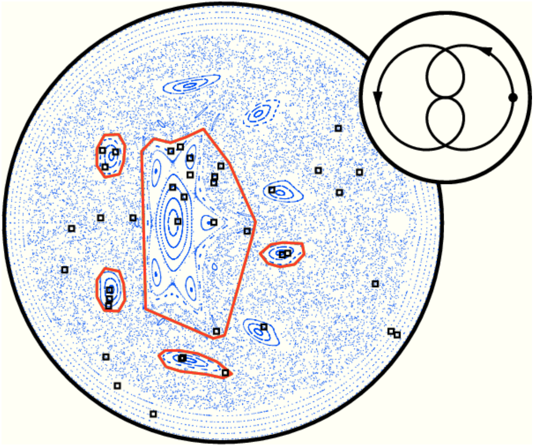
Run times in seconds:

# 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.

A physical example: Rod stirring device



[movie 2]

Conclusions

- Having trajectories 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 need good physical problems to try it on!
- See Thiffeault (2005, 2010) and soon preprint by Allshouse & Thiffeault.

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