

Lecture 28: The braidlab Matlab package

1 Installing braidlab

The package `braidlab` is defined inside a Matlab namespace, which are specified as subfolders beginning with a '+' character. The Matlab path must contain the folder that contains the subfolder `+braidlab`, and not the `+braidlab` folder itself:

```
>> addpath 'path to folder containing +braidlab'
```

To execute a braidlab *function*, either call it using the syntax `braidlab.function`, or import the whole namespace:

```
>> import braidlab.*
```

This allows invoking *function* by itself, without the `braidlab` prefix. For the remainder of this document, we assume this has been done and omit the `braidlab` prefix. The `addpath` and `import` commands can be added to `startup.m` to ensure they are executed at the start of every Matlab session.

2 A tour of braidlab

2.1 The braid class

`braidlab` defines a number of classes, most importantly `braid` and `loop`. The braid $\sigma_1\sigma_2^{-1}$ is defined by

```
>> a = braid([1 -2]) % defaults to 3 strings  
  
a = < 1 -2 >
```

which defaults to the minimum required strings, 3. The same braid on 4 strings is defined by

```
> a4 = braid([1 -2],4) % force 4 strings
a4 = < 1 -2 >
```

Two braids can be multiplied:

```
>> a = braid([1 -2]); b = braid([1 2]);
>> a*b, b*a

ans = < 1 -2 1 2 >

ans = < 1 2 1 -2 >
```

Powers can also be taken, including the inverse:

```
>> a^5, inv(a), a*a^-1

ans = < 1 -2 1 -2 1 -2 1 -2 1 -2 >

ans = < 2 -1 >

ans = < 1 -2 2 -1 >
```

Note that this last expression is the identity braid, but is not simplified. The method `compact` attempts to simplify the braid:

```
>> compact(a*a^-1)

ans = < e >
```

The method `compact` is based on the heuristic algorithm of Bangert *et al.* (2002), since finding the braid of minimum length in the standard generators is in general difficult (Paterson & Razborov, 1991).

The number of strings is

```
>> a.n

ans = 3
```

Note that

```
>> help braid
```

describes the class `braid`. To get more information on the `braid` constructor, invoke

```
>> help braid.braid
```

which refers to the method `braid` within the class `braid`. (Use `methods(braid)` to list all the methods in the class.) There are other ways to construct a `braid`, such as using random generators, here a braid with 5 strings and 10 random generators:

```
>> braid('random',5,10)

ans = < 1  4 -4  2  4 -1 -2  4  4  4 >
```

The constructor can also build some standard braids:

```
>> braid('halftwist',5)

ans = < 4  3  2  1  4  3  2  4  3  4 >
```

In Section 2.2 we will also show how to construct a braid from a trajectory data set. The `braid` class also handles equality of braids:

```
>> a = braid([1 -2]); b = braid([1 -2 2 1 2 -1 -2 -1]);
>> a == b

ans = 1
```

These are the same braid. Equality is determined efficiently by acting on loop (Dynnikov) coordinates (Dynnikov, 2002), as described by Dehornoy (2008). See Sections 2.3–2.4 for more details.

We can extract a subbraid by choosing specific strings: for example, if we take the 4-string braid $\sigma_1\sigma_2\sigma_3^{-1}$ and discard the third string, we obtain $\sigma_1\sigma_2^{-1}$:

```
>> a = braid([1 2 -3]);
>> subbraid(a,[1 2 4]) % subbraid using strings 1,2,4

ans = < 1 -2 >
```

There are a few methods that exploit the connection between braids and homeomorphisms of the punctured disk. Braids label *isotopy classes* of homeomorphisms, so we can assign a topological entropy to a braid:

```
>> entropy(braid([1 2 -3]))

ans = 0.8314
```

The entropy is computed by iterated action on a loop (Moussafir, 2006). This can fail if the braid is finite-order or has very low entropy:

```
>> entropy(braid([1 2]))
Warning: Failed to converge to requested tolerance; braid is
likely finite-order or has low entropy.
> In braid.entropy at 89

ans = 0
```

To force the entropy to be computed using the Bestvina–Handel train track algorithm Bestvina & Handel (1995), we add an optional parameter:

```
>> entropy(braid([1 2]), 'trains')

ans = 0
```

Note that for large braids the Bestvina–Handel algorithm is impractical. But when applicable it can also determine the Thurston–Nielsen type of the braid (Fathi *et al.*, 1979; Thurston, 1988; Casson & Bleiler, 1988; Boyland, 1994):

```
>> tntype(braid([1 2 -3]))

ans = pseudo-Anosov
>> tntype(braid([1 2]))

ans = finite-order
>> tntype(braid([1 2],4)) % reducing curve around 1,2,3

ans = reducible
```

`braidlab` uses Toby Hall’s implementation of the Bestvina–Handel algorithm (Hall, 2012).

Finally, we can also find the Burau matrix representation (Burau, 1936; Birman, 1975) of a braid:

```
>> burau(braid([1 -2]), -1)

ans = 1    -1
      -1    2
```

where the last argument (-1) is the value of the parameter t in the Laurent polynomials that appear in the entries of the Burau matrices.

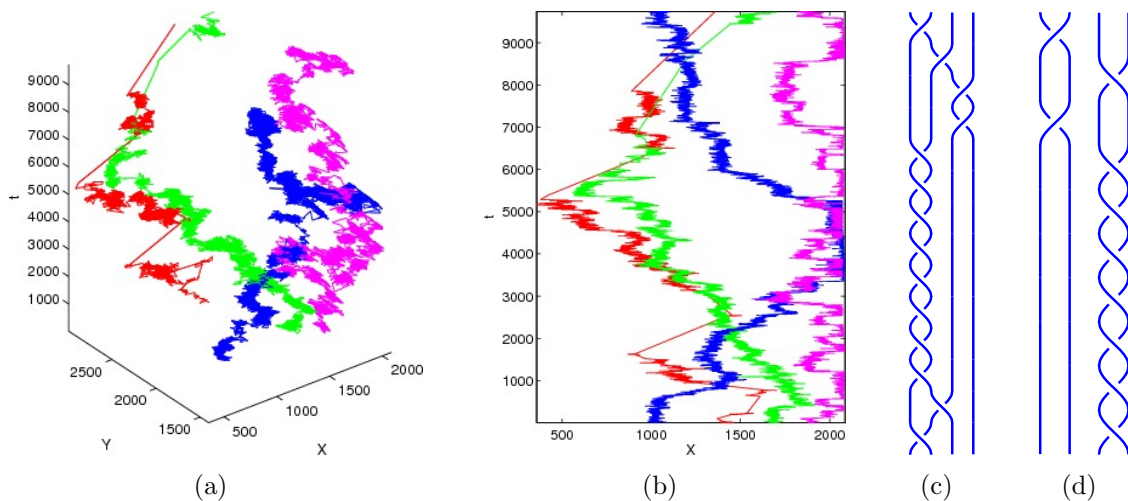


Figure 1: (a) A dataset of four trajectories, (b) projected along the X axis. (c) The compacted braid $\sigma_1^{-1}\sigma_2^{-1}\sigma_1^{-8}\sigma_3^2\sigma_2\sigma_1$ corresponding to the X projection in (b). (d) The compacted braid $\sigma_3^{-7}\sigma_1\sigma_3^{-1}\sigma_1$ corresponding to the Y projection, with closure enforced. The braids in (c) and (d) are conjugate.

2.2 Constructing a braid from data

One of the main purposes of `braidlab` is to analyze two-dimensional trajectory data using braids. We can assign a braid to trajectory data by looking for *crossings* along a projection line (Thiffeault, 2005, 2010). The braid constructor allows us to do this easily.

The folder `testing` contains a dataset of trajectories, from laboratory data for granular media Puckett *et al.* (2012). From the `testing` folder, we load the data:

```
>> clear; load testdata
>> whos
  Name          Size          Bytes  Class  Attributes
  XY            9740x2x4          623360 double
  ti            1x9740            77920  double
```

Here `ti` is the vector of times, and `XY` is a three-dimensional array: its first component specifies the timestep, its second specifies the X or Y coordinate, and its third specifies one of the 4 particles. Figure 1(a) shows the X and Y coordinates of these four trajectories, with time plotted vertically. Figure 1(b) shows the same data, but

projected along the X direction. To construct a braid from this data, we simply execute

```
>> b = braid(XY);  
>> b.length  
  
ans = 894
```

This is a very long braid! But Figure 1(b) suggests that this is misleading: many of the crossings are ‘wiggles’ that cancel each other out. Indeed, if we attempt to shorten the braid:

```
>> b = compact(b)  
  
b = < -1 -2 -1 -1 -1 -1 -1 -1 -1 -1 3 3 2 1 >  
>> b.length  
  
ans = 14
```

we find the number of generators (the length) has dropped to 14! We can then plot this shortened braid as a braid diagram using `plot(b)` to produce Figure 1(c). The braid diagram allows us to see topological information clearly, such as the fact that the second and third particles undergo a large number of twists around each other; we can check this by creating a subbraid with only those two strings:

```
>> subbraid(bX,[2 3])  
  
ans = < -1 -1 -1 -1 -1 -1 -1 -1 >
```

which shows that the winding number between these two strings is -4 .

The braid was constructed from the data by assuming a projection along the X axis (the default). We can choose a different projection by specifying an optional angle for the projection line; for instance, to project along the Y axis we invoke

```
>> b = braid(XY,pi/2); % project onto Y axis  
>> b.length  
  
ans = 673  
>> b.compact  
  
ans = < -3 -3 -3 -3 -3 -3 -3 1 -3 >
```

In general, a change of projection line only changes the braid by conjugation (Boylan, 1994; Thiffeault, 2010). We can test for conjugacy:

```
>> bX = compact(braid(XY,0)); bY = compact(braid(XY,pi/2));
>> conjtest(bX,bY) % test for conjugacy of braids

ans = 0
```

The braids are not conjugate. This is because our trajectories do not form a ‘true’ braid: the final points do not correspond exactly with the initial points, as a set. If we truly want a rotationally-conjugate braid out of our data, we need to enforce a closure method:

```
>> XY = closure(XY); % close braid and avoid new crossings
>> bX = compact(braid(XY,0)), bY = compact(braid(XY,pi/2))

bX = < -1 -2 -1 -1 -1 -1 -1 -1 -1 -1 3 3 2 1 >
bY = < -3 -3 -3 -3 -3 -3 -3 1 -3 1 >
```

This default closure simply draws line segments from the final points to the initial points in such a way that no new crossings are created in the X projection. Hence, the X -projected braid \mathbf{bX} is unchanged by the closure, but here the Y -projected braid \mathbf{bY} is longer by one generator (\mathbf{bY} is plotted in Figure 1(d)). This is enough to make the braids conjugate:

```
>> [~,c] = conjtest(bX,bY) % ~ means discard first return arg
c = < 3 2 >
```

where the optional second argument \mathbf{c} is the conjugating braid, as we can verify:

```
>> bX == c*bY*c^-1

ans = 1
```

There are other ways to enforce closure of a braid (see `help closure`), in particular `closure(XY, 'mindist')`, which minimizes the total distance between the initial and final points.

Note that `conjtest` uses the library *CBraid* (Cha, 2011) to first convert the braids to Garside canonical form (Birman & Brendle, 2005), then to determine conjugacy. This is very inefficient, so is impractical for large braids.

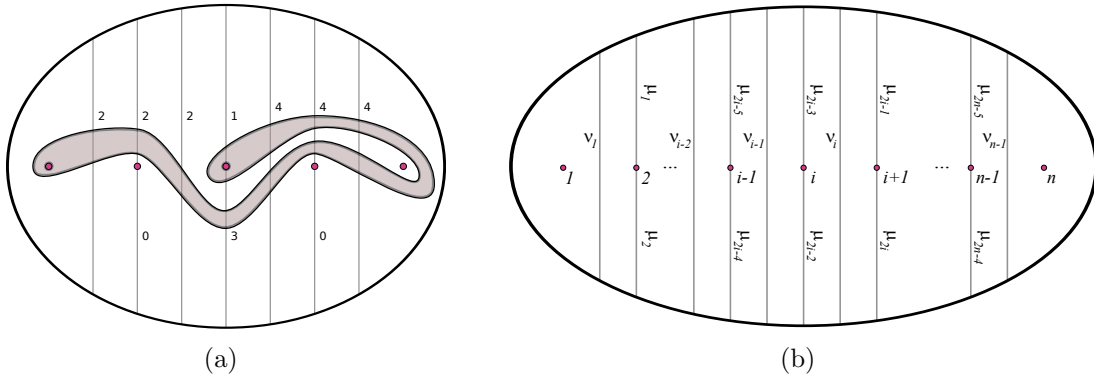


Figure 2: (a) A simple close loop in a disk with $n = 5$ punctures. (b) Definition of intersection numbers μ_i and ν_i . [From Thiffeault (2010).]

2.3 The loop class

A simple closed loop on a disk with 5 punctures is shown in Figure 2(a). We consider equivalence classes of such loops under homotopies relative to the punctures. In particular, the loops are *essential*, meaning that they are not null-homotopic or homotopic to the boundary or a puncture. The *intersection numbers* are also shown in Figure 2(a): these count the minimum number of intersections of an equivalence class of loops with the fixed vertical lines shown. For n punctures, we define the intersection numbers μ_i and ν_i in Figure 2(b).

Any given loop will lead to a unique set of intersection numbers, but a general collection of intersection numbers do not typically correspond to a loop. It is therefore more convenient to define

$$a_i = \frac{1}{2} (\mu_{2i} - \mu_{2i-1}), \quad b_i = \frac{1}{2} (\nu_i - \nu_{i+1}), \quad i = 1, \dots, n-2. \quad (1)$$

We then combine these in a vector of length $(2n-4)$,

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

which gives the *loop coordinates* (or *Dynnikov coordinates*) for the loop. (Some authors such as Dehornoy (2008) give the coordinates as $(a_1, b_1, \dots, a_{n-2}, b_{n-2})$.) There is now a bijection between \mathbb{Z}^{2n-4} and essential simple closed loops (Dynnikov, 2002; Moussafir, 2006; Hall & Yurttaş, 2009; Thiffeault, 2010). Actually, *multiloops*: loop coordinates can describe unions of disjoint loops.

Let's create the loop in Figure 2(a) as a `loop` object:

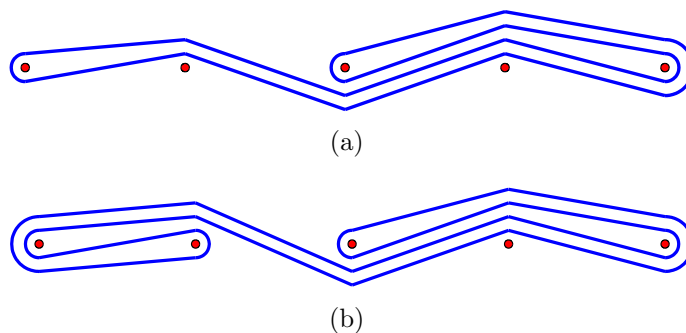


Figure 3:

```
>> l = loop([-1 1 -2 0 -1 0])
l = (( -1 1 -2 0 -1 0 ))
```

Figure 3(a) shows the output of the `plot(l)` command. Now we can act on this loop with braids. For example, we define the braid `b` to be σ_1^{-1} with 5 strings, corresponding to the 5 punctures, and then act on the loop `l` by using the multiplication operator:

```
>> b = braid([-1],5); % one generator with 5 strings
>> b*l % act on a loop with a braid

ans = (( -1 1 -2 1 -1 0 ))
```

Figure 3(b) shows `plot(b*l)`. The first and second punctures were interchanged counterclockwise (the action of σ_1^{-1}), dragging the loop along.

The minimum length of an equivalence class of loops is determined by assuming the punctures are one unit of length apart and have zero size. After pulling tight the loop on the punctures, it is thus made up of unit-length segments. The minimum length is thus an integer. For the loop in Figure 3(a),

```
>> minlength(l)

ans = 12
```

The `entropy` method computes the topological entropy of a braid by repeatedly acting on a loop, and monitoring the growth rate of the loop.

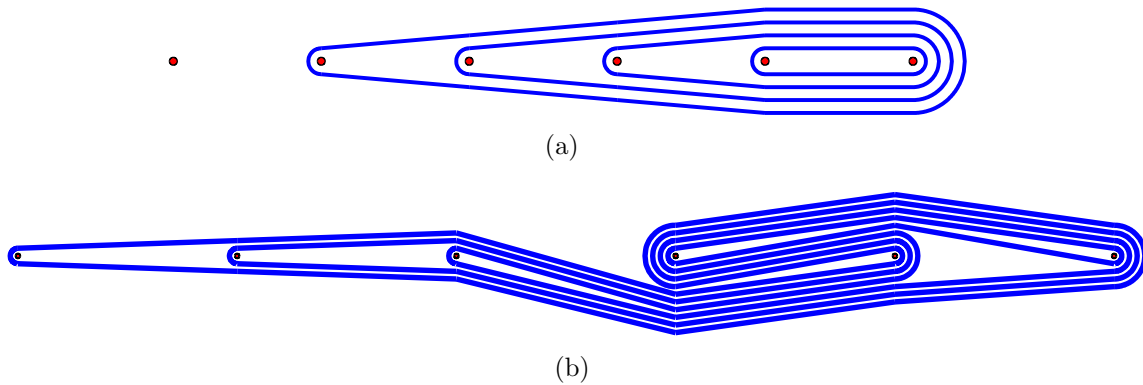


Figure 4: (a) The multiloop created by `loop(5)`. (b) The multiloop `b*loop(5)`, where `b` is the braid $\sigma_1\sigma_2\sigma_3\sigma_4^{-1}$.

```
>> b = braid([1 2 3 -4]);
% apply braid 100 times to l, then compute growth of length
>> log(minlength(b^100*1)/minlength(1)) / 100

ans = 0.7637
>> entropy(b)

ans = 0.7672
```

The entropy value returned by `entropy(b)` is more precise, since that method monitors convergence and adjusts the number of iterations accordingly.

2.4 Loop coordinates for a braid

The loop coordinates allow us to define a unique normal form for braids. Consider the multiloop depicted in Figure 4(a), which is the output of `plot(loop(5))`. Notice that `loop(5)` defaulted to a loop on a disk with 6 punctures. The reason is that this default multiloop is used to define loop coordinates for braids. The extra puncture is regarded as the outer boundary of the disk, and the loops form a generating set for the fundamental group of the disk with 5 punctures. The canonical loops coordinates for braids exploit the fact that two braids are equal if and only if they act the same way on the fundamental group of the disk. Hence, if we take a braid and act on `loop(5)`,

```
>> b = braid([1 2 3 -4]);
```

```
>> b*loop(5)
```

```
ans = (( 0 0 3 -1 -1 -1 -4 3 ))
```

then the set of numbers $((0 0 3 -1 -1 -1 -4 3))$ can be thought of as *uniquely* characterizing the braid. It is this property that is used to rapidly determine equality of braids (Dehornoy, 2008). (The loop `b*loop(5)` is plotted in Figure 4(b).) The same loop coordinates for the braid can be obtained without creating an intermediate loop with

```
>> loopcoords(b)
```

```
ans = (( 0 0 3 -1 -1 -1 -4 3 ))
```

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