


what do fluid mixing and taffy pulling have in common?

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Hassan Aref Memorial Lecture
Department of Biomedical Engineering and Mechanics, VirginiaTech
Blacksburg, VA, 27 October 2016

Supported by NSF grant CMMI-1233935



Boyland-Aref-Stremler stirring device



Introduced 'topological stirring' to the world.



play movie



play movie

[Boyland, P. L., Aref, H., & Stremler, M. A. (2000). *J. Fluid Mech.* **403**, 277–304;
Simulations by M. D. Finn, S. E. Tumas, and J-LT.]

the taffy puller



Taffy is a type of candy.

Needs to be **pulled**: this aerates it and makes it lighter and chewier.

We can assign a **growth**: length multiplier per period.

[movie by M. D. Finn]

play movie



four-pronged taffy puller



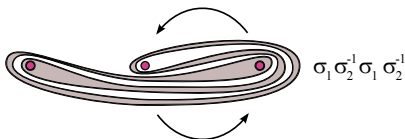
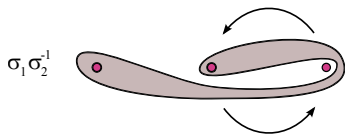
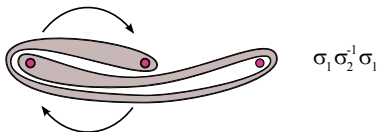
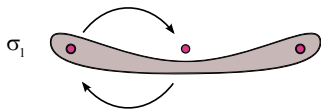
play movie

<http://www.youtube.com/watch?v=Y7t1HDSquVM>

[MacKay (2001); Halbert & Yorke (2014)]

Boyland-Aref-Stremler device as a simple taffy puller

initial



[Remark for later: each rod moves in a 'figure-eight' shape.]



[Matlab: demo1 using braidlab]

Let's count alternating left/right folds. The sequence is

$$\#folds = 1, 1, 2, 3, 5, 8, 13, 21, 34, \dots$$

What is the rule?

$$\#folds_n = \#folds_{n-1} + \#folds_{n-2}$$

This is the famous **Fibonacci sequence**, F_n .

how fast does the taffy grow?



It is well-known that for large n ,

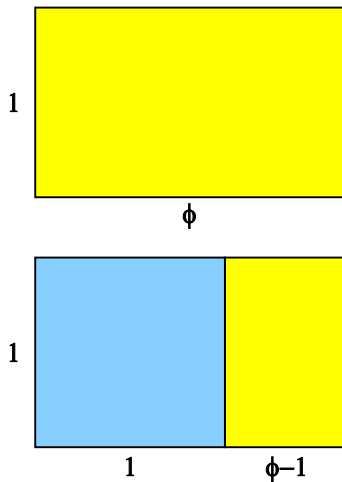
$$\frac{F_n}{F_{n-1}} \rightarrow \phi = \frac{1 + \sqrt{5}}{2} = 1.6180\dots$$

where ϕ is the **Golden Ratio**, also called the **Golden Mean**.

So the ratio of lengths of the taffy between two successive steps is ϕ^2 , where the squared is due to the left/right alternation.

Hence, the **growth factor** for this taffy puller is

$$\phi^2 = \phi + 1 = 2.6180\dots$$



A rectangle has the proportions of the Golden Ratio if, after taking out a square, the remaining rectangle has the same proportions as the original:

$$\frac{\phi}{1} = \frac{1}{\phi - 1}$$

a slightly more complex taffy puller



[Matlab: demo2 using braidlab]

Now let's swap our prongs twice each time.

We get for the number of left/right folds

$$\#folds = 1, 2, 5, 12, 29, 70, 169, 408 \dots$$

This sequence is given by

$$\#folds_n = 2\#folds_{n-1} + \#folds_{n-2}$$

For large n ,

$$\frac{\#folds_n}{\#folds_{n-1}} \rightarrow \chi = 1 + \sqrt{2} = 2.4142 \dots$$

where χ is the **Silver Ratio**, a much less known number.

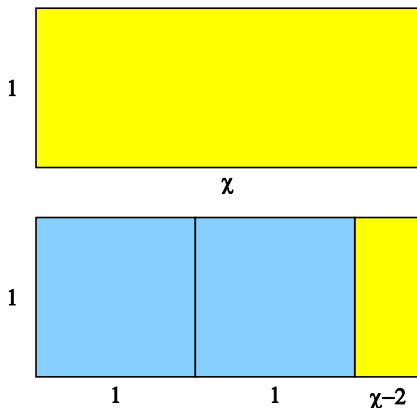
Hence, the **growth factor** for this taffy puller is

$$\chi^2 = 2\chi + 1 = 5.8284 \dots$$

the Silver Ratio, χ



A rectangle has the proportions of the Silver Ratio if, after taking out **two squares**, the remaining rectangle has the same proportions as the original.



$$\frac{\chi}{1} = \frac{1}{\chi - 2}$$

$$\chi = 1 + \sqrt{2} = 2.4142 \dots$$

Both major taffy puller designs (3- and 4-rod) have growth χ^2 .



These quadratic numbers are reminiscent of invertible linear maps on the torus T^2 , such as **Arnold's Cat Map**:

$$\begin{pmatrix} x \\ y \end{pmatrix} \mapsto \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \pmod{1}, \quad x, y \in [0, 1]^2$$

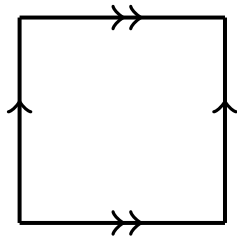
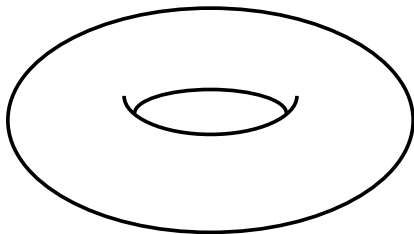
The largest eigenvalue of the matrix

$$M = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$$

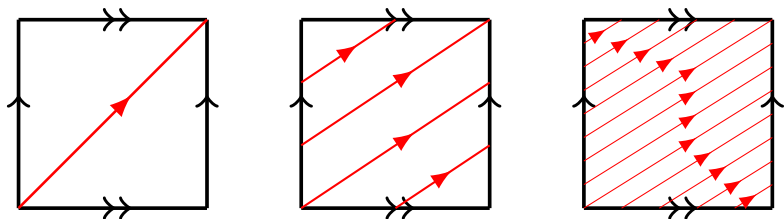
is ϕ^2 .

What's the connection between taffy pullers and these maps?

The 'standard model' for the torus is the biperiodic unit square:



The Cat Map stretches loops exponentially:



This loop will stand in for a piece of taffy.

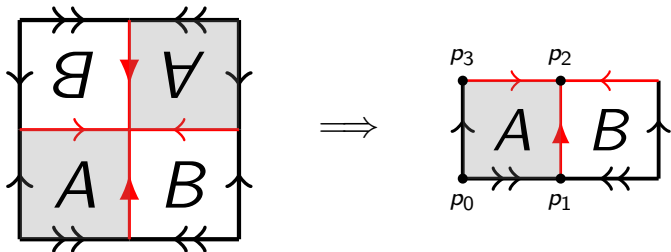
hyperelliptic involution



Consider the linear map $\iota(x) = -x \bmod 1$. This map is called the **hyperelliptic involution** ($\iota^2 = \text{id}$).

Construct the quotient space

$$S = T^2 / \iota$$

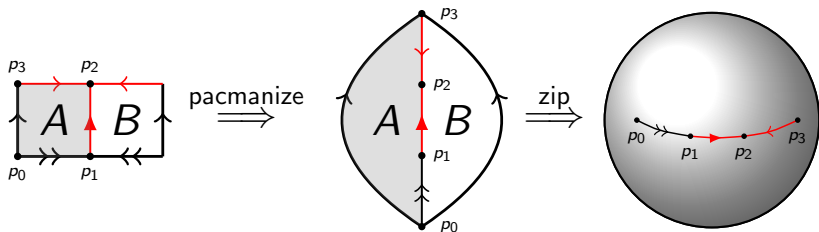


Claim: the surface S (right) is a sphere with four **punctures**!

sphere with four punctures



Here's how we see that S is a sphere:



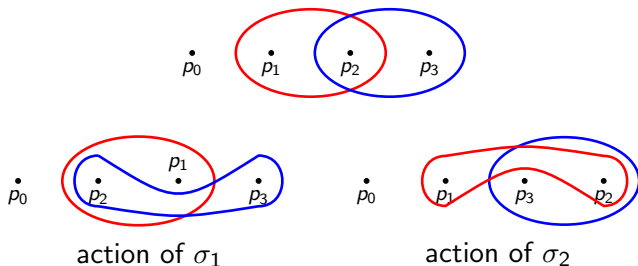
The punctures $p_{1,2,3}$ are the **rods of our taffy puller**. The puncture p_0 is like a point at infinity on the plane.

Linear maps **commute with ι** , so all linear torus maps 'descend' to taffy puller motions.

Any taffy puller motion can be represented as a product of

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix}$$

and their inverses, known as **Dehn twists**.



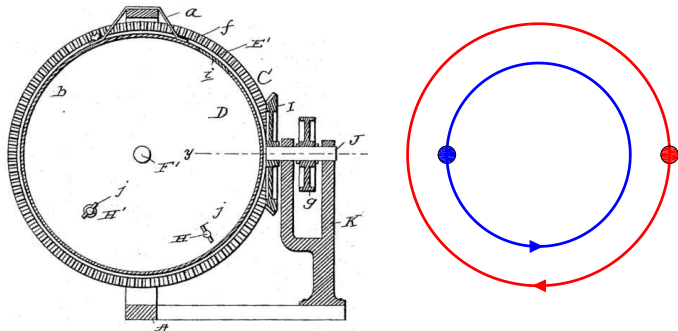
These can also be view as generators for the **braid group** for 3 strings.

the history of taffy pullers



But who invented the well-known designs for taffy pullers? [Google patents](#) is an awesome resource.

The very first: Firchau (1893)



This is a terrible taffy puller. It was likely never built, but plays an important role in the looming...

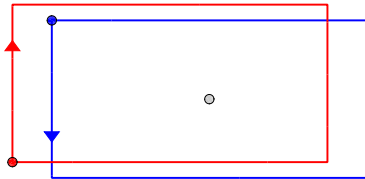
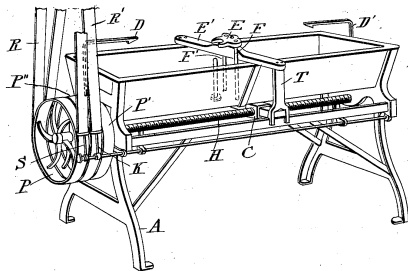
A black and white historical photograph showing a large fleet of aircraft carriers and their escorts at sea. The carriers are visible in the lower third of the frame, with a massive formation of aircraft flying overhead in a coordinated pattern. The text "taffy patent wars" is overlaid in red in the center of the image.

taffy patent wars

The first true taffy puller



I think Herbert M. Dickinson (1906, but filed in 1901) deserves the title of inventor of the first taffy puller:



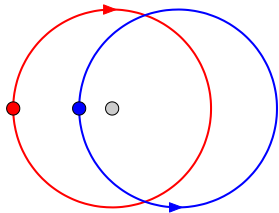
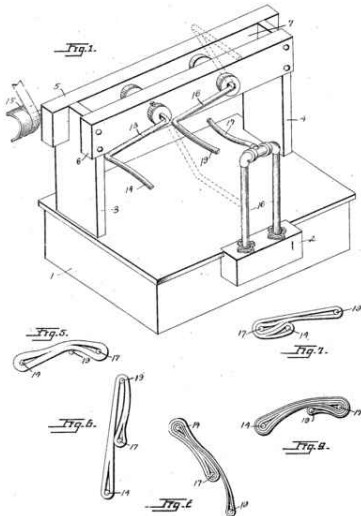
Awkward design: the moving rods get 'tripped' each cycle. But it is topologically the same as the 3-rod device still in use today.

There seem to be questions as to whether it ever worked, or if it really pulled taffy rather than mixing candy.

The modern 3-rod design



Robinson & Deiter (1908) greatly simplified this design to one still in use today.



The uncontested taffy magnate of the early 20th century was Herbert L. Hildreth of Maine.



The Hotel Velvet in Old Orchard, Maine

**Hildreth's Original
— and Only —
Velvet Candy**

Is now put up in Triple Sealed Packages. Moisture, Germ and Dust Proof

For sale by the Jobbing trade everywhere. Send for Price List and Samples. The finest seller on earth. Has been on the market nearly 25 years. Nothing like it. Address

H. L. HILDRETH CO.
Franklin and Battery-march Sts.
Boston, Mass.

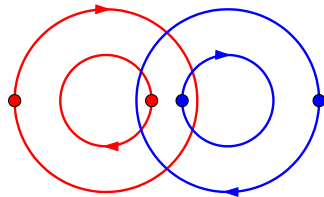
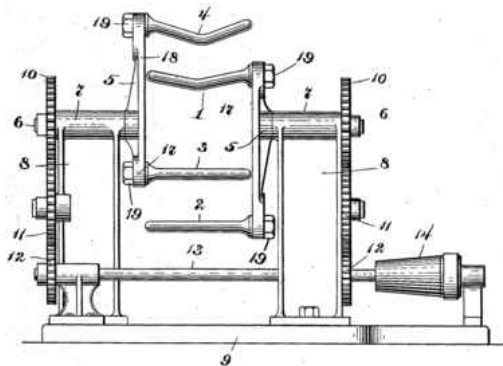
The Confectioners Gazette (1914)

His hotel was on the beach, and taffy was popular at such resorts. He sold it wholesale as well.

the 4-rod design

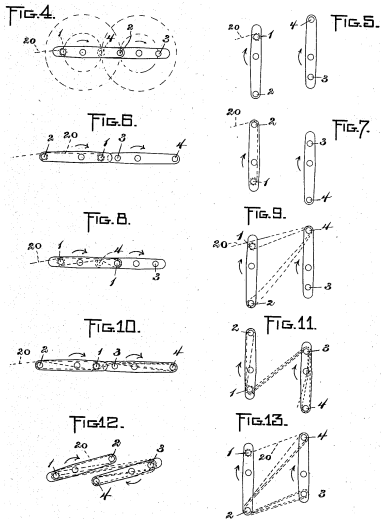


The first 4-rod design is by Thibodeau (1903, filed 1901), an employee of Hildreth.

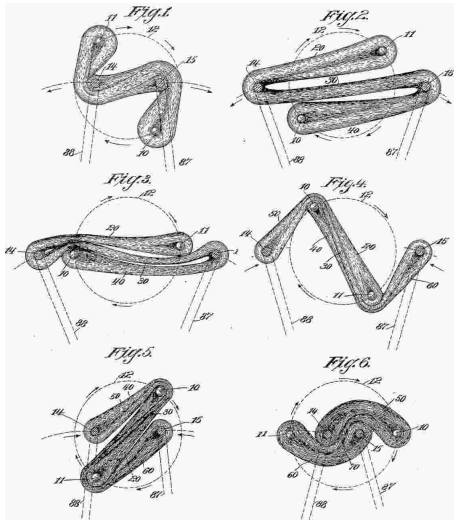


Hildreth was not pleased by this but bought the patent for \$75,000 (about two million of today's dollars).

the best patents have beautiful diagrams



Thibodeau (1903)



Richards (1905)



So many concurrent patents were filed that lawsuits ensued for more than a decade. Shockingly, the taffy patent wars went all the way to the **US Supreme Court**. The opinion of the Court was delivered by **Chief Justice William Howard Taft** (*Hildreth v. Mastoras*, 1921):

*The machine shown in the Firchau patent [has two pins that] pass each other twice during each revolution [...] and move in concentric circles, but do not have the relative in-and-out motion or Figure 8 movement of the Dickinson machine. With only two hooks there could be no lapping of the candy, because there was no third pin to re-engage the candy while it was held between the other two pins. The movement of the two pins in concentric circles might stretch it somewhat and stir it, **but it would not pull it in the sense of the art.***

The Supreme Court opinion displays the fundamental insight that at least three rods are required to produce some sort of rapid growth.

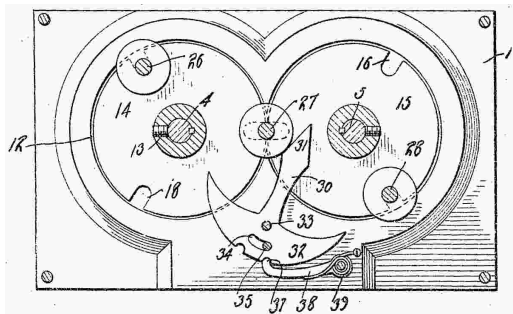
the quest for the Golden ratio



Is it possible to build a device that realizes the **simplest taffy puller**, with growth ϕ^2 ?

The problem is that each rod **moves in a Figure-eight!** This is hard to do mechanically. (**Mark just used his hands!.**)

After some digging, found the patent of Nitz (1918):

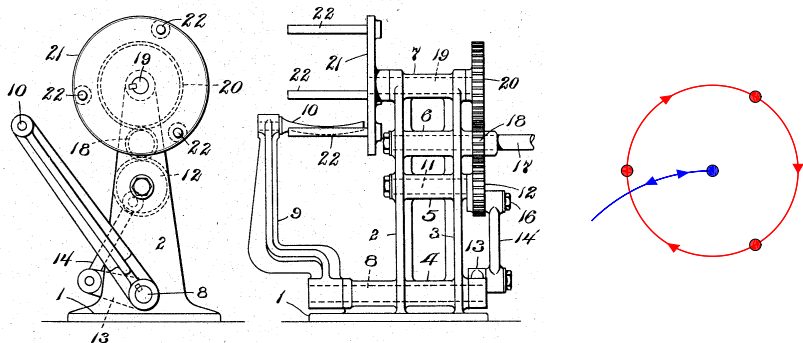


This is the **Boyland-Aref-Stremler device!**

the quest for the Golden ratio (2)

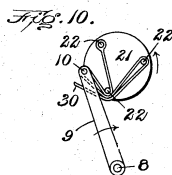
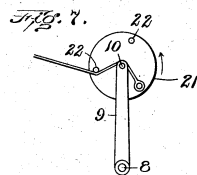
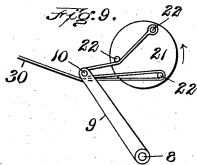
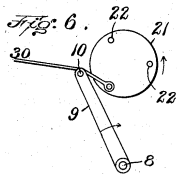
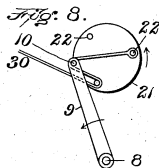
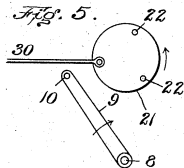


There is actually an earlier 4-rod design by Thibodeau (1904) which has $(\text{Golden ratio})^2$ growth:



Since it uses four rods to get a quadratic growth, the map must involve a **branched cover of the torus** by a theorem of Franks & Rykken (1999). (The same happens for the 4-rod vs 3-rod 'standard' taffy pullers.)

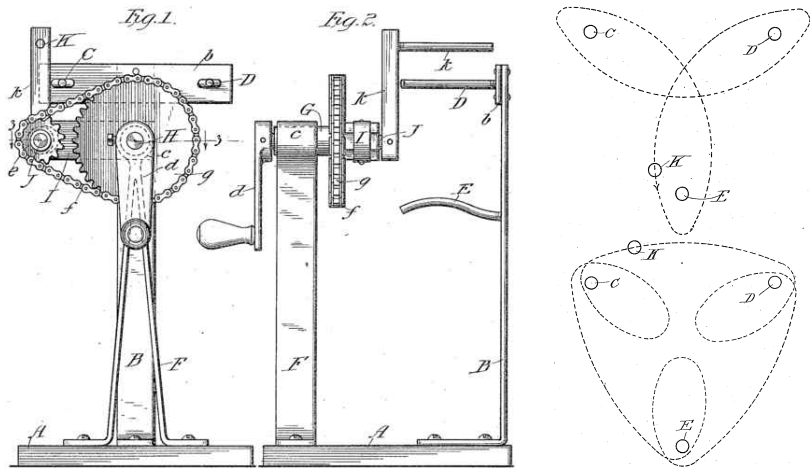
the quest for the Golden ratio (3)



Thibodeau (1904) once again gives very nice diagrams for the action of his taffy puller.

(He has at least 5 patents for taffy pullers.)

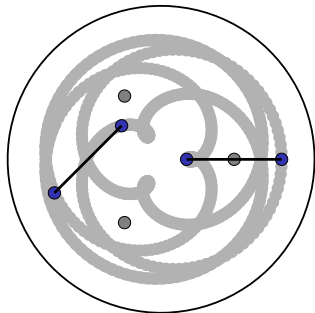
A few designs are based on 'planetary' gears, such as McCarthy (1916):



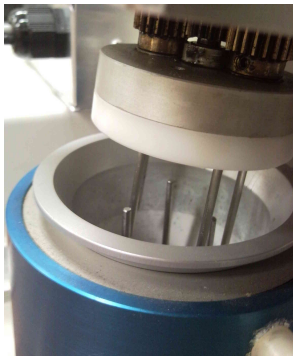
the mixograph



A modern planetary design is the **mixograph**, a device for measuring the properties of dough:



play movie



[Department of Food Science, University of Wisconsin. Photos by J-LT.]



The mixograph measures the resistance of the dough to the pin motion.

This is graphed to determine properties of the dough, such as water absorption and 'peak time.'

the mixograph as a braid



Encode the topological information as a sequence of **generators of the Artin braid group B_n** .

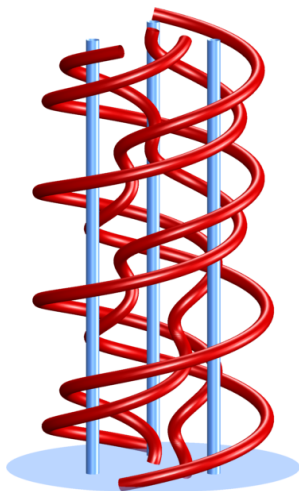
Equivalent to the 7-braid

$$\sigma_3 \sigma_2 \sigma_3 \sigma_5 \sigma_6^{-1} \sigma_2 \sigma_3 \sigma_4 \sigma_3 \sigma_1^{-1} \sigma_2^{-1} \sigma_5$$

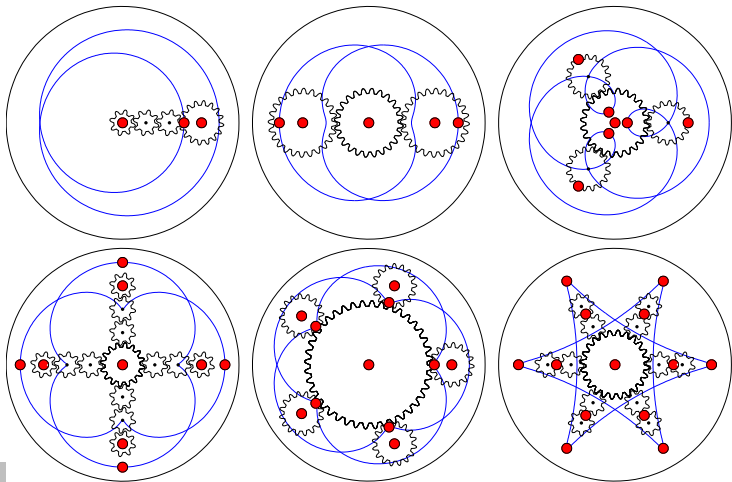
We feed this braid to the **Bestvina–Handel algorithm**, which determines the **Thurston type** of the braid (**pseudo-Anosov**) and finds the **growth** as the largest root of

$$x^8 - 4x^7 - x^6 + 4x^4 - x^2 - 4x + 1$$

$$\simeq 4.186$$



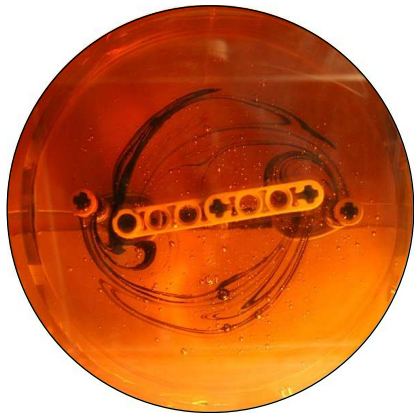
As part of an optimization procedure, we (Finn & Thiffeault, 2011) designed a family of planetary mixers with **silver ratio** expansion:



play movie



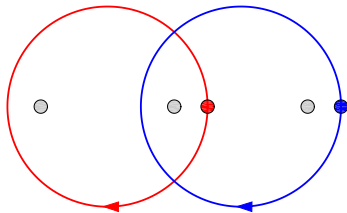
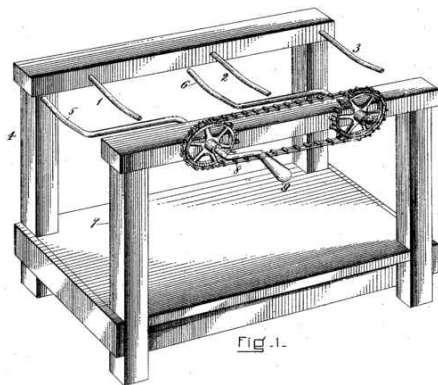
play movie



play movie

[See Finn, M. D. & Thiffeault, J.-L. (2011). *SIAM Rev.* **53** (4), 723–743 for proofs, heavily influenced by work on π_1 -stirrers of Boyland, P. L. & Harrington, J. (2011). *Algeb. Geom. Topology*, **11** (4), 2265–2296.]

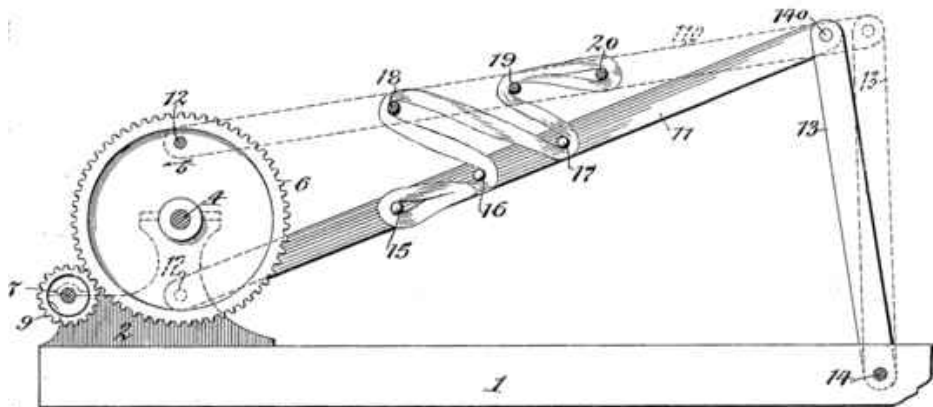
There remains many patents that I call 'exotic' which use nonstandard motions: such as Jenner (1905):



exotic designs (2)



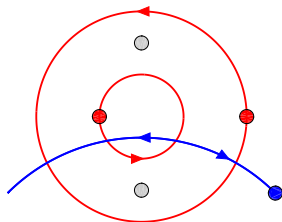
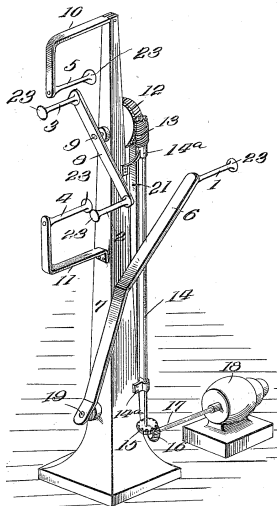
Shean & Schmelz (1914):



exotic designs (3)



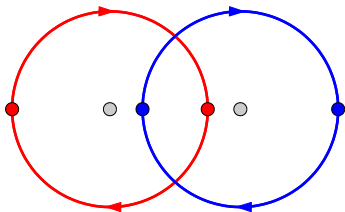
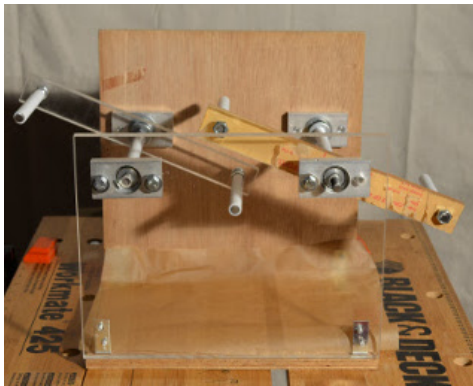
My personal favorite, McCarthy & Wilson (1915):



let's try our hand at this



Six-rod design with Alex Flanagan:

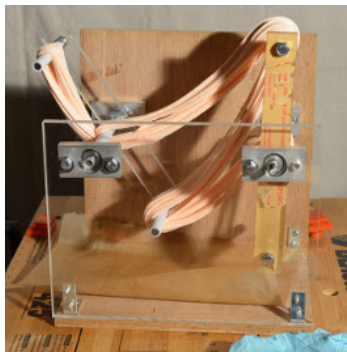
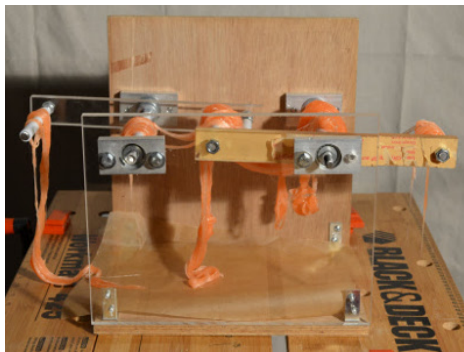


The software tools allow us to rapidly try designs. This one is simple and has huge growth (13.9 vs 5.8 for the standard pullers).

making taffy is hard



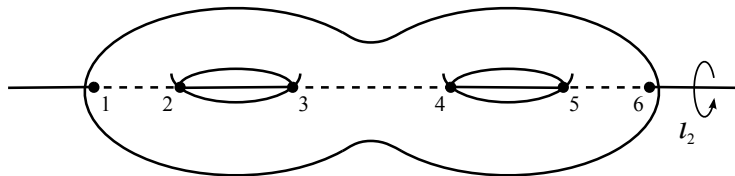
Early efforts yielded mixed results: . . . but eventually we got better at it



play movie

(BTW: The physics of candy making is fascinating. . .)

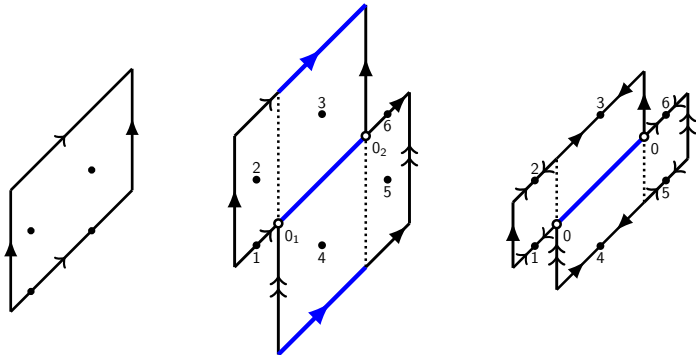
The six rods are fixed points of a hyperelliptic involution of a genus-two surface:



a cut-up genus-two surface

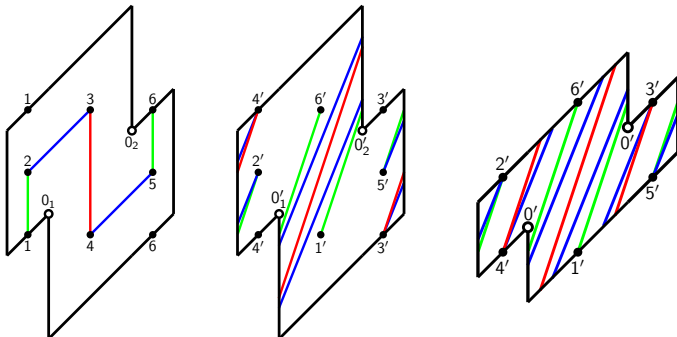


Two tori are glued to make the genus-two surface:

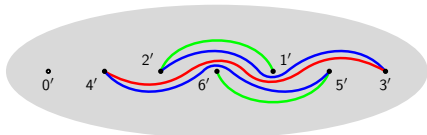
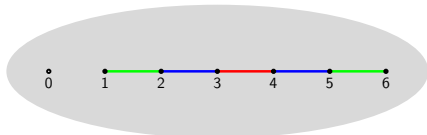


A quotient by the involution then gives a sphere with 6 distinguished points.

map on a genus-two surface



$$\phi(x) = \begin{pmatrix} -1 & -1 \\ -2 & -3 \end{pmatrix} \cdot x$$





- My real interest is in fluid mixing, in particular of viscous substances.
- The taffy pullers illustrate that mixing is a **combinatorial process**, akin to **shuffling**.
- The taffy designs also pop up in 'serious' **chemical mixers**.
- The topological dynamics methods pioneered by Thurston and first applied to practical problems by Hassan with Boyland-Stremmer allows us to understand these rod motions in great detail.
- For example, in addition to the growth, there is a **measure** that tells us how taffy is distributed on the rods.
- **pseudo-Anosov maps** themselves are still the subject of intense study.



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