Frustration: inability of a system as a whole to reach a stress-free equilibrium state.
There can be no complex motion from elastic deformations without frustration.
Rolling motion can be created from zero elastic energy modes or ZEEMs of soft robots which are examples of complicated motion due to frustration.

Zeem theory: An elastic object must have positive (stretching) and negative (compressing) prestrains to have a Zeem. These prestrains can be created from geometry for example by bending a straight nylon fiber to a ring which cause negative and positive prestrains on two different sides. The Zeems can also be created from active deformation such as the bending deformation due to buckling. The frustration from these prestrains is called static frustration

The elastic energy does not change by moving in a ZEEM but a flux of energy from an external source in the form of heat or light is needed to overcome the energy barrier from material viscous damping, friction and other energy dissipating effects. The flux of external energy creates another frustration called dynamic frustration and the interaction between the static and dynamic frustration creates the Zeem motion. The flux of energy must be perpendicular to the prestrain gradient for the Zeem to happen.

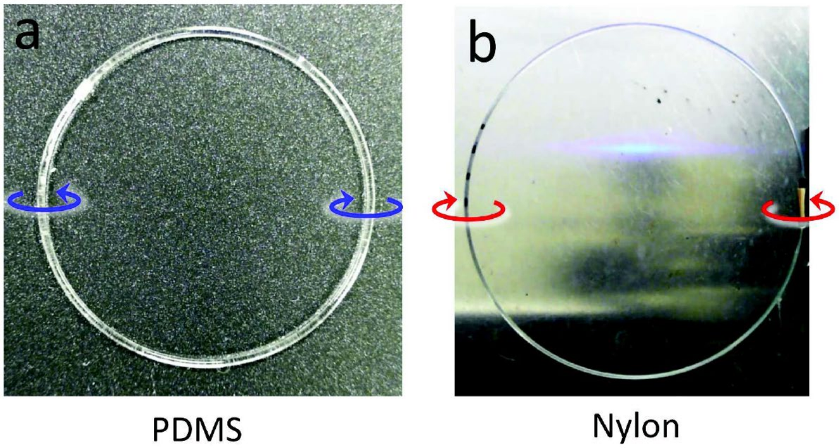
Coupling coefficient: If for the external field of T (temperature- variable of the thermal field) and the induced strain of ϵ_{ii}, we have the equation $\epsilon_{ii} = \alpha T$, α is called the coupling coefficient which in the case of a thermal field is the thermal expansion coefficient.
If the coupling coefficient is a scalar which means the material is isotropic, then the sign of α will determine whether the material will bend away from or towards the direction of the energy flux. It explains why the sign of the thermal expansion coefficient α gives the direction of rotation for the fiberdrive or curvature for the fiberboid for different materials.

Annealing: Annealing is the gradual warming of the objects to remove their undesired prestrains usually trapped during the manufacturing process which disrupt their motion and prevent them to move in their Zeems. Annealing is a necessary preprocessing in almost all experiments related to the motion of soft robots in Zeems.

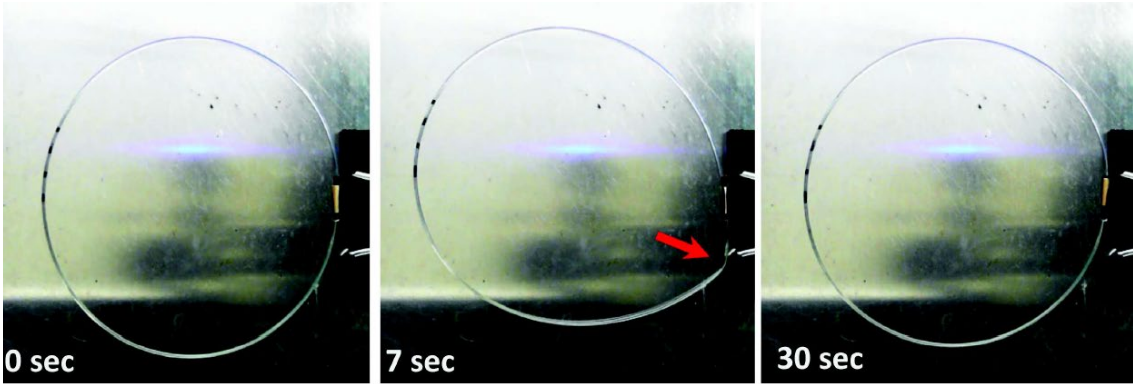
Ring or torus made of Nylon fishing line or Fiberdrive or Toroidal Fiberdrive: with diameters of 0.6mm and 0.8mm, closed into rings of radius ranging from 2cm to 6cm via a small brass tube.
Put at the hot surface of 160-180℃, Unidirectional motion
Besides nylon 6, also made of PVDF polyvinylidene difluoride or PDMS polydimethylsiloxane.
Challenging to build especially in small sizes.

Easy and Robust annealing process, high resistance to high temperatures (Rarely lose their Zeems)
Very rarely at 190-195℃rings suffer an irreversible damage that leads to a blocking of their rotation without any visible kink or obvious defect. Nevertheless, the majority of the rings stay functional and rotating for days and have a self-healing mechanism. Once properly annealed, a ring can be subjected to high driving temperatures (up to 180 ℃) without any problems even after several days of inactivity.
The rings are gently annealed by raising the temperature just beyond the onset of rolling over the course of a few minutes in order to relieve mechanical prestresses entrapped during their fabrication.

Fiberdrives constructed out of nylon-6 and PVDF turn outward while those constructed out of PDMS turn inward. The direction in which the ring moves is dictated by the sign of the thermal expansion coefficient. Nylon is contracting upon heating and thus rotates inwards whereas the thermally expanding PDMS rotates in the opposite direction.
For high running temperatures, the angular velocity is almost independent of the radius of the torus.



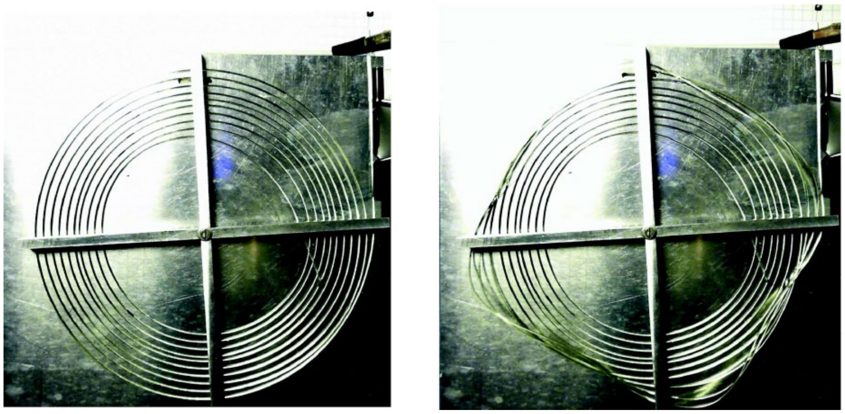
Experimental realizations of the fiberdrive with a) PDMS (radius 2cm, thickness 0.6mm) and b) Nylon (radius 6cm, thickness 0.6mm).



Collective spontaneous self-healing of defects in a circular fiber motor from nylon-6 rotating at 190◦C. A strong deformation defect (kink) emerges at time t = 7 s and persists for several seconds. The continued collective rotation of the fiber leads to a complete self-healing at a later time (t = 30 s)

The Spiral Fiberdrive or Spiral Fiber Motor: Toroidal fiberdrives are difficult to interconnect due to their closed geometry which makes them poor candidates to do work but they can be connected in a parallel by an Aluminum holder to make a spiral fiberdrive capable of applying large torques and doing work by for example lifting a weight ten times heavier than itself.
Spiral fiberdrives have to be annealed more carefully and slowly due to frictional interactions with the holder (gentle raising temperature in 10-15 minutes from 100-160℃) C) and occasional gentle stirring of the fiber (with a silicone brush) along its tangents to relieve built-up strains and to unpin it from the holder.

On top of its very robust operation and it scalability (ability to have many spires even in 3D), another feature of the spiral fiberdrive is the ability to act as a storage device, an elastic battery. When rigidly stalled and prevented from rotating (by clamping one of the its free end), the fiber's free end continues to turn for several minutes and hundreds of turns before stalling. This process harvests the residual thermal energy from pumping and stores it within the material itself in the form of torsional elastic energy. When the fixed end is released, this stored energy can be retrieved.



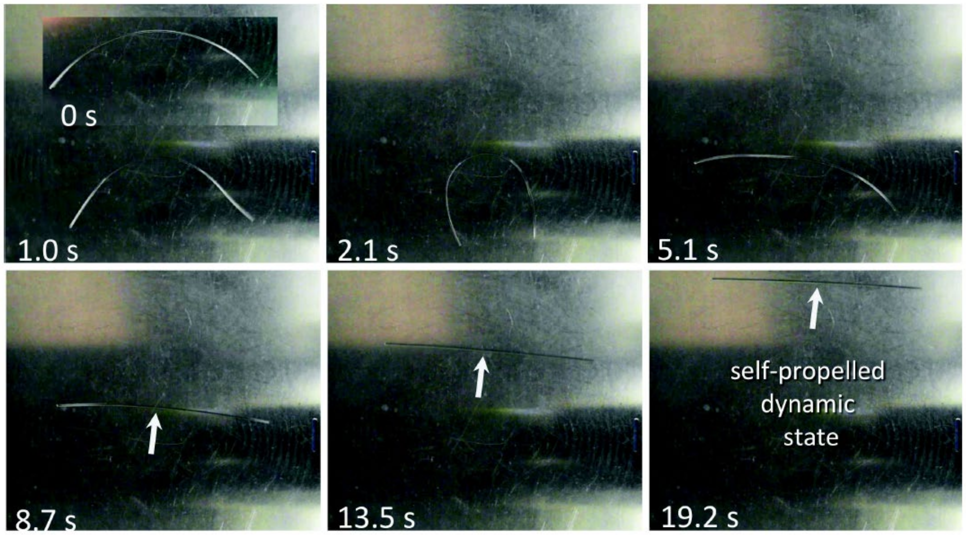
When clamping the spiral at one end, it continues to operate, storing elastic energy. The longer tests were performed until a buckling event as depicted on the right happened, the tests were stopped to prevent mechanical damage to the spirals.

Straight piece of polymer fiber or Linear Fibers Fiberboid: Bidirectional, random initial direction, changes direction when facing obstacles.
Could be made of nylon 6, PVDF, PDMS, Silicone rubber and spaghetti, Easy to build and miniaturize.
Not suited to do mechanical work because of random bidirectionality.

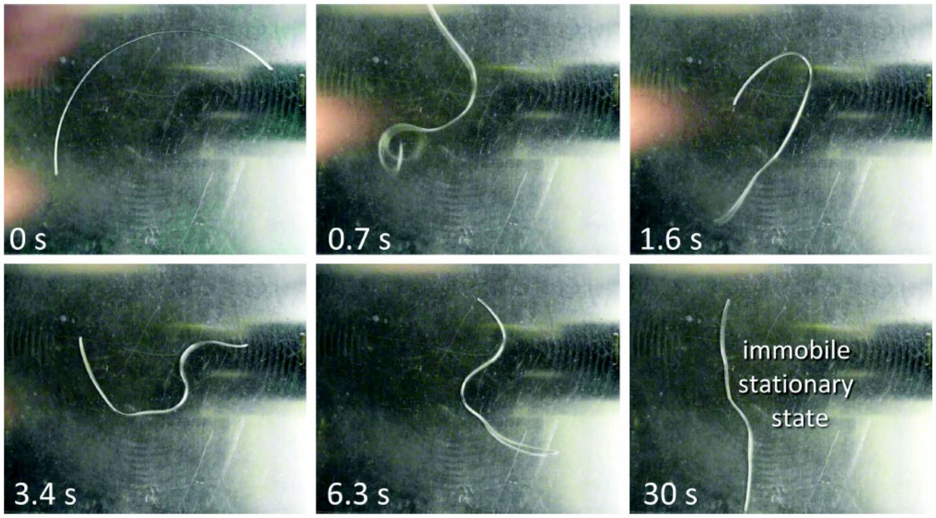
Annealing is much more important in linear fibers than the toroidal fiberdrives, their resistance to high temperatures is lower and unlike the toroidal fiberdrives they do not have a self-healing or self-repair mechanism.
Nylon-6 fibers with diameters ranging from 800 down to 120 μm are gently annealed by slowly heating the fiber on the heating plate from their onset temperature of rolling (around 100-110 ℃ for the 600 and 800 μm diameter fiber) up to their optimal running temperatures of 180-185℃ In a typical annealing procedure, the temperature is gently raised over the course of several minutes so that the fiber gradually liberates defects and prestresses via the process of combined heating and their spontaneous rolling which is called training.
The annealing of thinner nylon-6 fibers, below 0.2 mm in radius, becomes increasingly delicate and structural defects (like bends, kinks and twisted helical sections) appear more often. Consequently, annealing of thinner samples has to be a slower procedure compared with the thicker fibers.
For the PVDF fiber samples the annealing is more delicate than for nylon-6. A modified annealing protocol respecting the lower PVDF melting temperature is followed, with a temperature rise from 130℃ up to 170℃ at a slower heating rate of 1 K/min. After annealing PVDF fibers move with velocities comparable to their nylon-6 counterparts. The PDMS fiber samples do not need any annealing, probably because their preparation process involves curing them at relatively high temperature for some time.

Skipping the first gradual training run and instead directly exposing the fibers to temperatures higher than their onset temperature (of 140℃-180℃) results in a rapid reshaping of the fiber and catastrophic deformations which leads in most cases to very poorly mobile or completely immobile fibers.

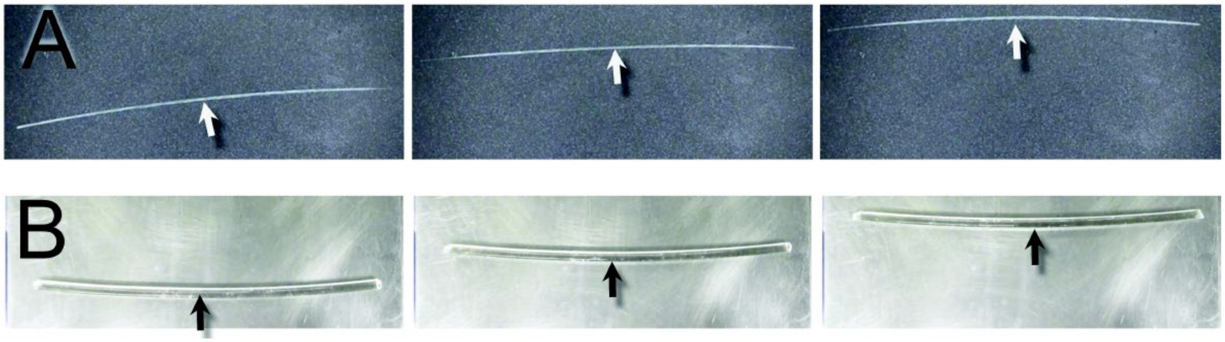
The total length of the fiber plays a certain role in their ability to roll smoothly and reproducibly. Occasionally, at temperature very close to the onset of rolling motion, shorter samples of PVDF and nylon-6 fibers (5 cm in length and below) become stuck in a metastable out-of plane deformation. They stay suspended above the surface with only two points of contact (their two ends) with the plate for a few seconds. The motion is then intermittent and prone to more frequent direction reversal. Although the pumping is in principle sufficient to drive the fibers, the fibers are not confined in the plane by gravity in this case. This behavior is never observed for the PDMS samples since their positive thermal expansion coefficient makes it so that only one point of contact with the plane re- main upon deformation. This effect is also observed when attempting to run water-driven fiberboids



Slow annealing of a 800 μm nylon fiber at 110◦C results in some transient reshaping and eventually within the time course of 10-20 seconds leads to an ideally straight and rolling fiber.

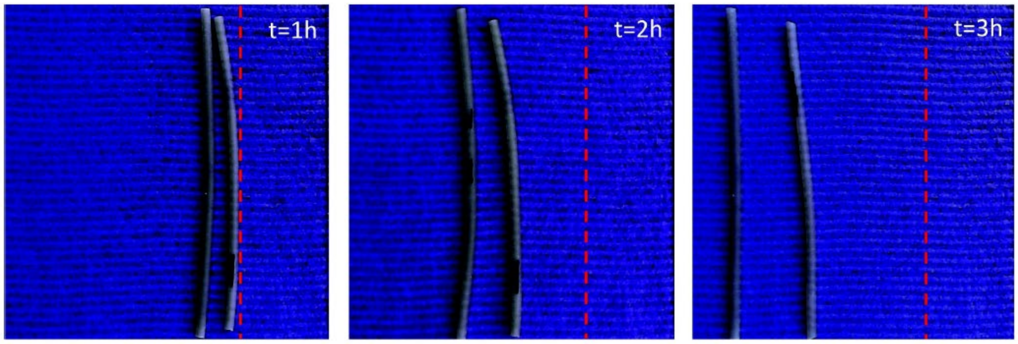


Exposing a nylon fiber (800 μm) directly to an elevated temperature (180◦C) results in rapid uncontrolled reshaping. The final shape remains stationary and does not move or roll over the surface.



Rolling motion of a nylon-6 rod (diameter 0.6 mm, length 12 cm) (A) and a PDMS rod (diameter 3 mm, length 11 cm) (B).

Spaghetti: Move much faster with flux of water evaporation than flux of heat
After several minutes on a hot surface and being put on a room temperature surface, it still moves even faster than before and in a reverse direction.



Macaroni noodles rolling on the surface of a wet sponge-like material. Pasta is a versatile tool to demonstrate the fiberboid effect. Here it is driven by an evaporation flux. The time scales are four orders of magnitude slower than the thermal fiberboid but it is similar same physics that powers the motion.

Another candidate shape to have zeems mentioned but not explained in detail is the mobius strip

Material Properties:

Nylon 6: with diameters ranging from 0.12mm to 0.8mm, Most robust and cheapest material, ”Caperlan 4 x 4”, supplier Decathlon, France, has the thermal expansion coefficient along the fiber axis of $\alpha = -1.9 \times 10^{-4} K^{-1}$ between 120 and 180 °C. $T_{melt} = 215$°C

PVDF: ”Phen-X-Fluorocarbone” fishing line fibers, supplier De-cathlon, France; diameter 0.5 mm
$T_{melt} = 177$°C

PDMS: The PDMS samples are prepared from a two-part kit that consists of liquid components (Rhodorsil RTV141 A+B (Bluestar)). The base and curing agents are mixed in a weight ratio of ten parts base to one part curing agent, stirring the mixture to homogenize for about 2 minutes. The mixture is then placed in a vacuum chamber for 30 minutes to remove the air bubbles. The final PDMS filaments are formed in glass tubes (capillaries and glass pipettes) that are gently fragmented after the curing process, that lasts for 2h at 80◦C. This PDMS rubber has a longitudinal expansion coefficient of $\alpha = 3.3 \times 10^{-4} K^{-1}$

The PDMS, PVDF and nylon rings are held together with short pieces of thermo-contracting PVDF shrink tubes or metallic brass tubes.

Experiment setup: The experimental setup for all experiments consists in a tabletop hot plate ((IKA®RCT basic IKAMAG^{TM}control) on top of which an Aluminum plate (15cmx15cmx4mm) was placed to homogenize the thermal contact.

All data are acquired with a webcam (Microsoft Lifecam studio 1080p) connected to a laptop and the resulting movies are analyzed with ImageJ

Dynamic mechanical thermal analysis (DMTA) tests were carried out with an Instron E3000 dynamic tensile machine

In order to analyze the structural features of the fibers, their crystallinity and anisotropy, wide-angle X-ray scattering (WAXS) experiments were performed using a Rigaku S-MAX3000 equipped with a Rigaku MicroMax-007HF copper rotating anode generator (12 kW, 40 kV, 300 mA) with radiation of wavelength $\lambda_{CuK\text{Đ}}$ = 0.15418 nm. The scattering intensities were collected by a Fujifilm BAS-MS 2025 imaging plate system (20 cm × 25 cm, 50 µm resolution) and a 2D Triton-200 X-ray gas-filled multi-wire detector (120 mm diameter, 100 µm resolution).