Russia IYPT

Artificial muscle

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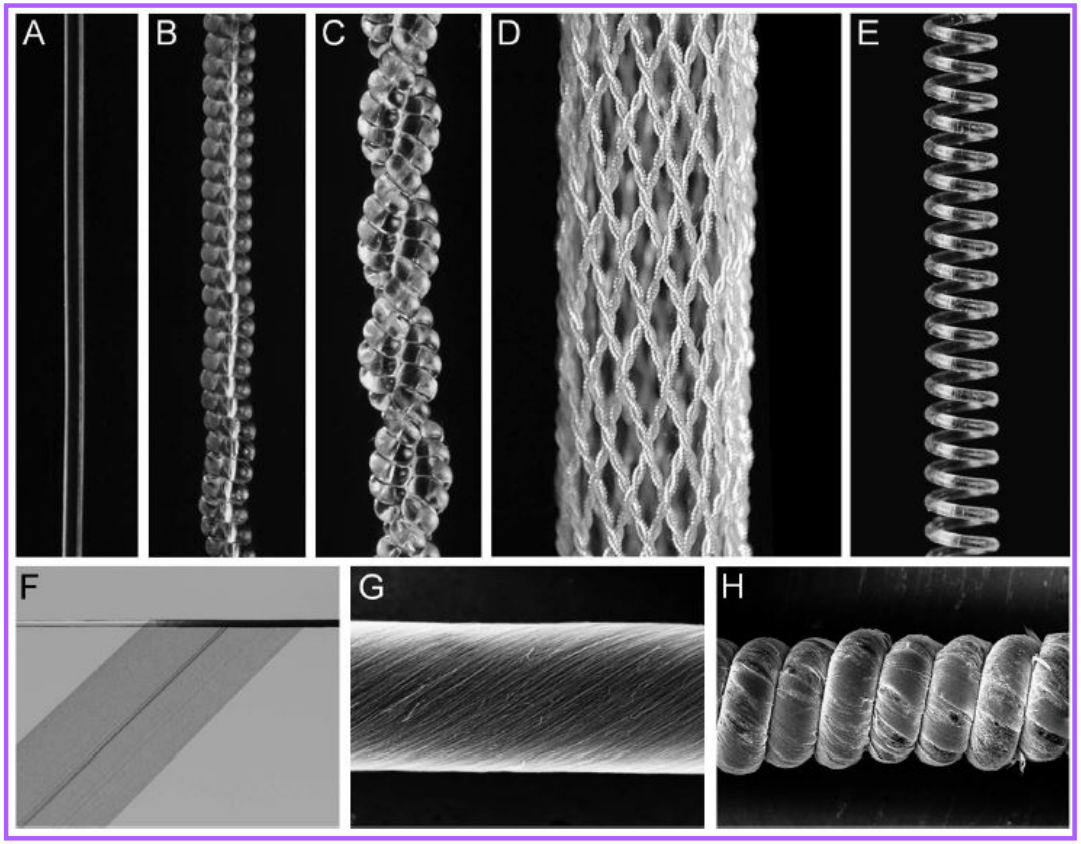
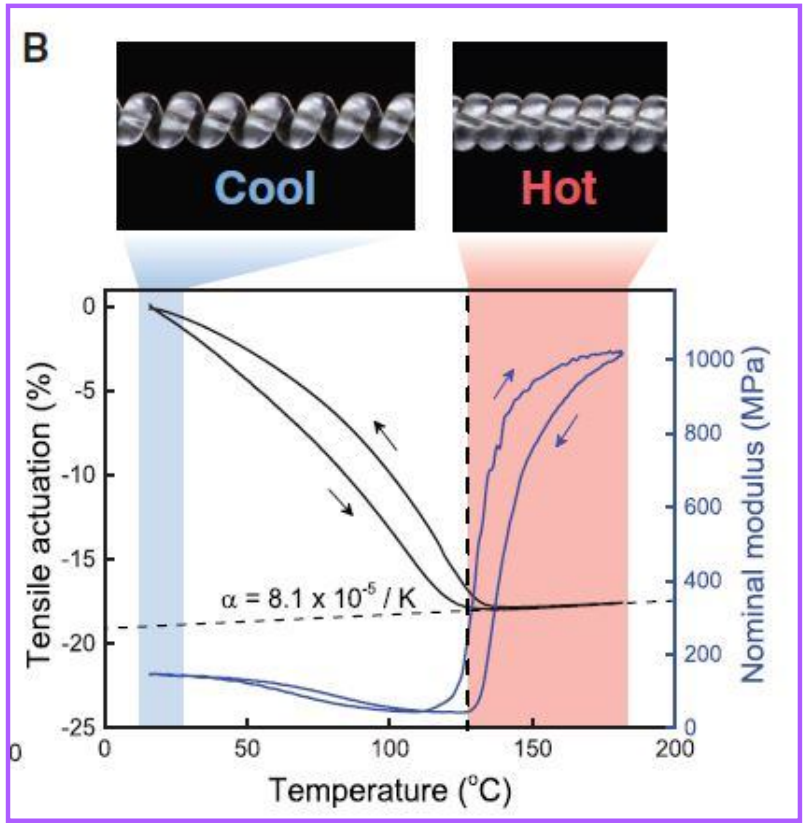
The problem

Attach a polymer fishing line to an electric drill and apply tension to the line. As it twists, the fibre will form tight coils in a spring-like arrangement. Apply heat to the coils to permanently fix that spring-like shape. When you apply heat again, the coil will contract. Investigate this ‘artificial muscle’.

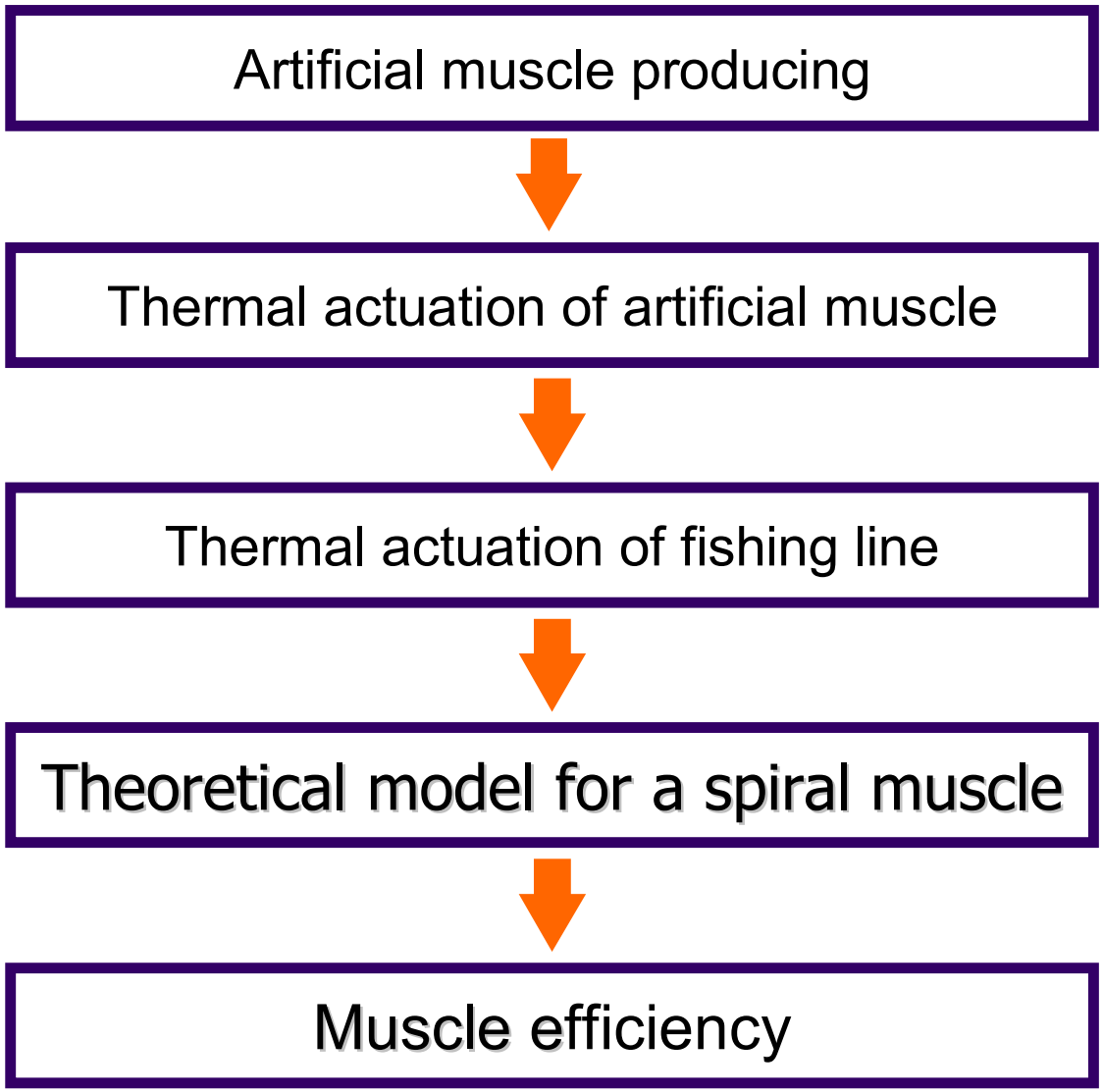
Previous investigation





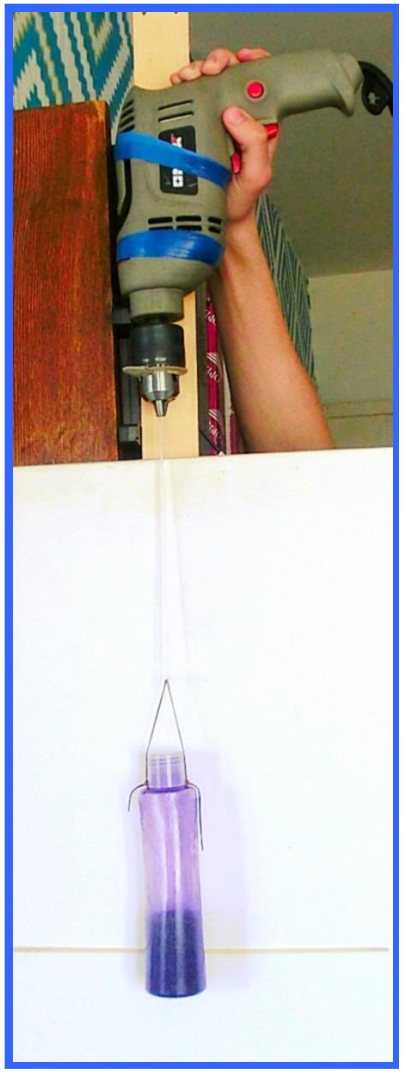
Haines C.S. *et al.* (2014) “Artificial muscles from fishing line and sewing thread”. *Science* **343**, 868–872.

Outline of the report



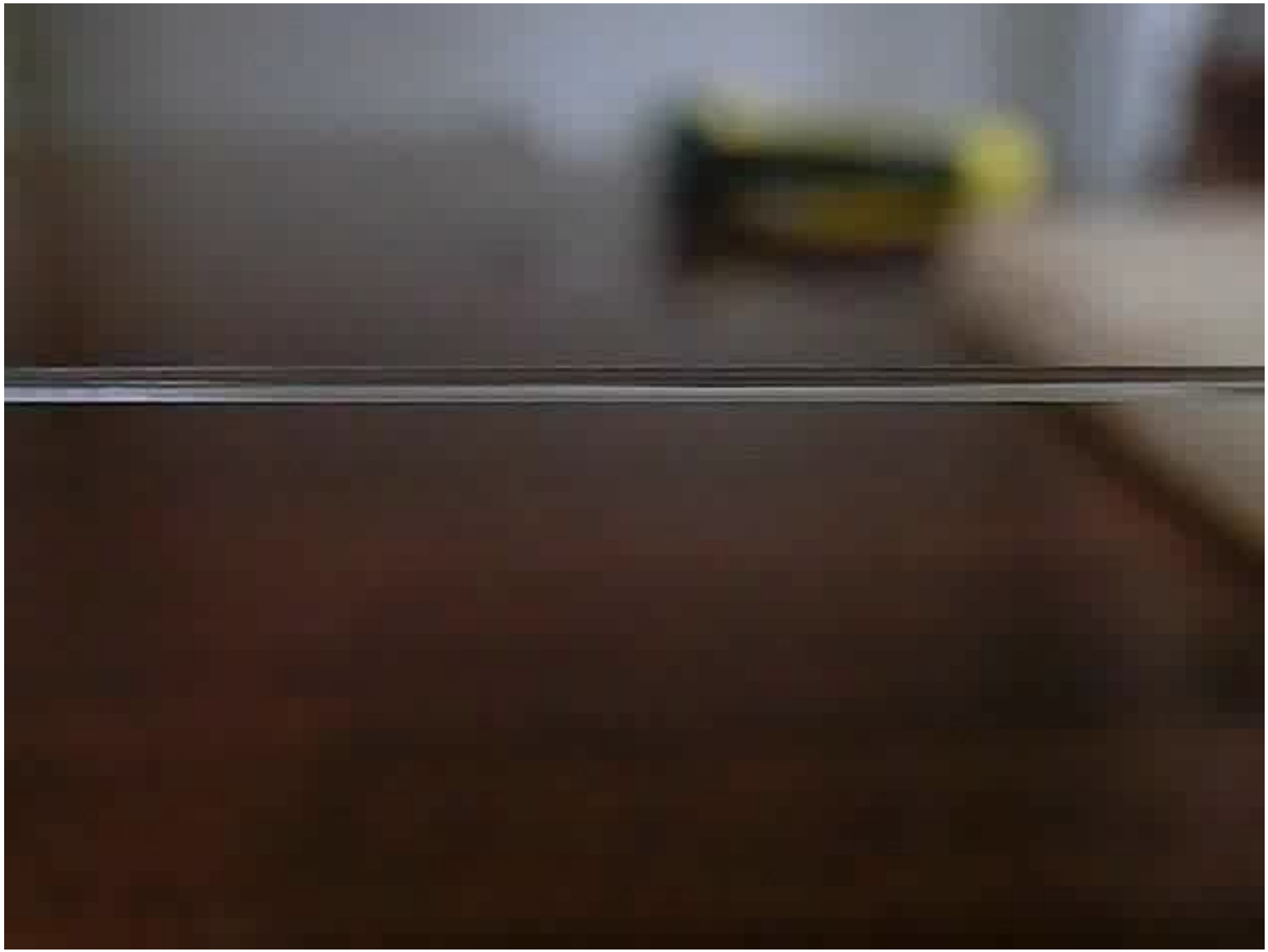
Producing of a spiral “muscle”

Fishing line twisting under load

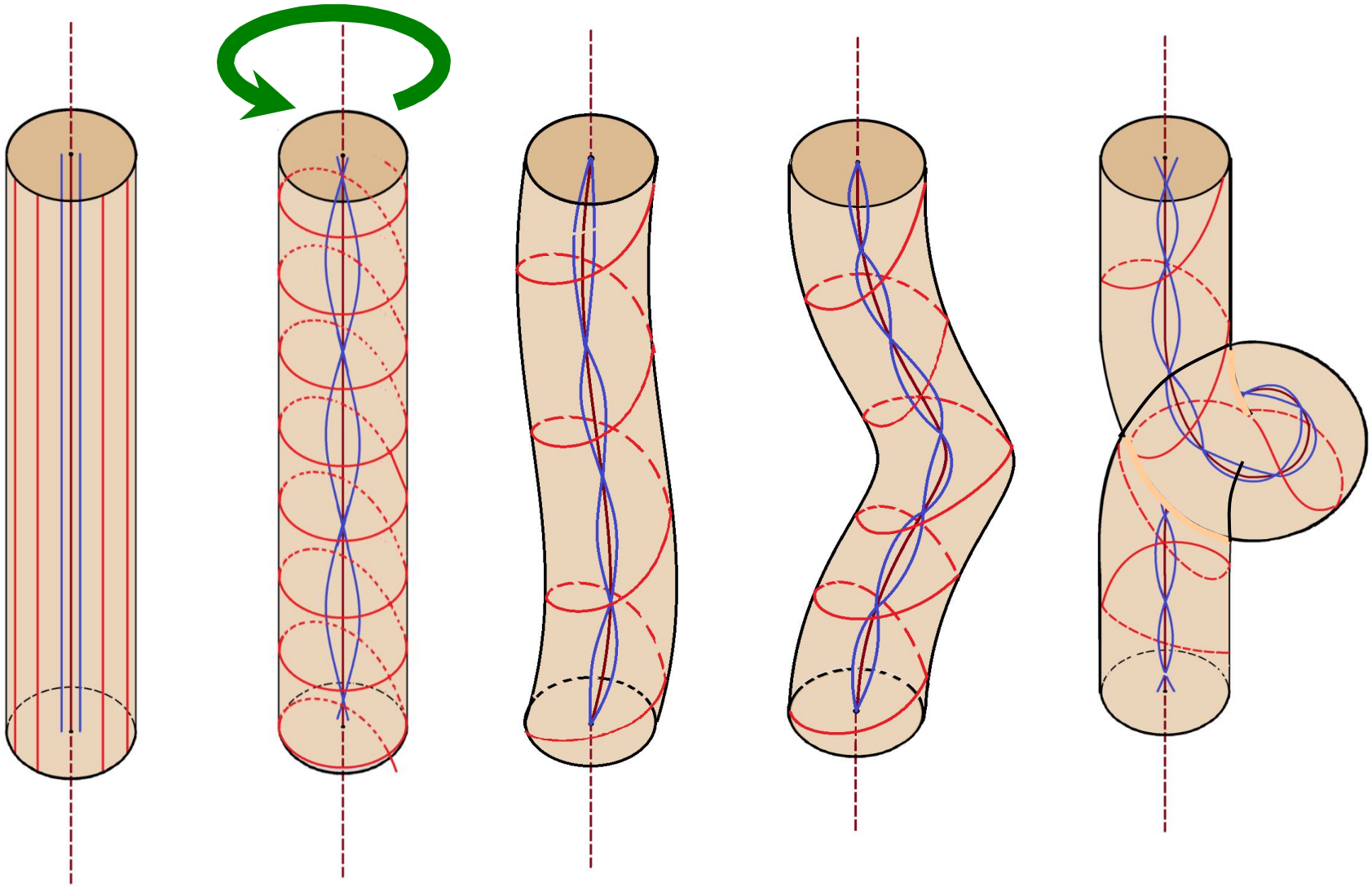


- To produce a spiral, we need a suitable load *F*.
- If the load is too high, a fishing line breaks during a process.
- If the load is too small, a fishing line is twisted in loops.

Spiral coiling

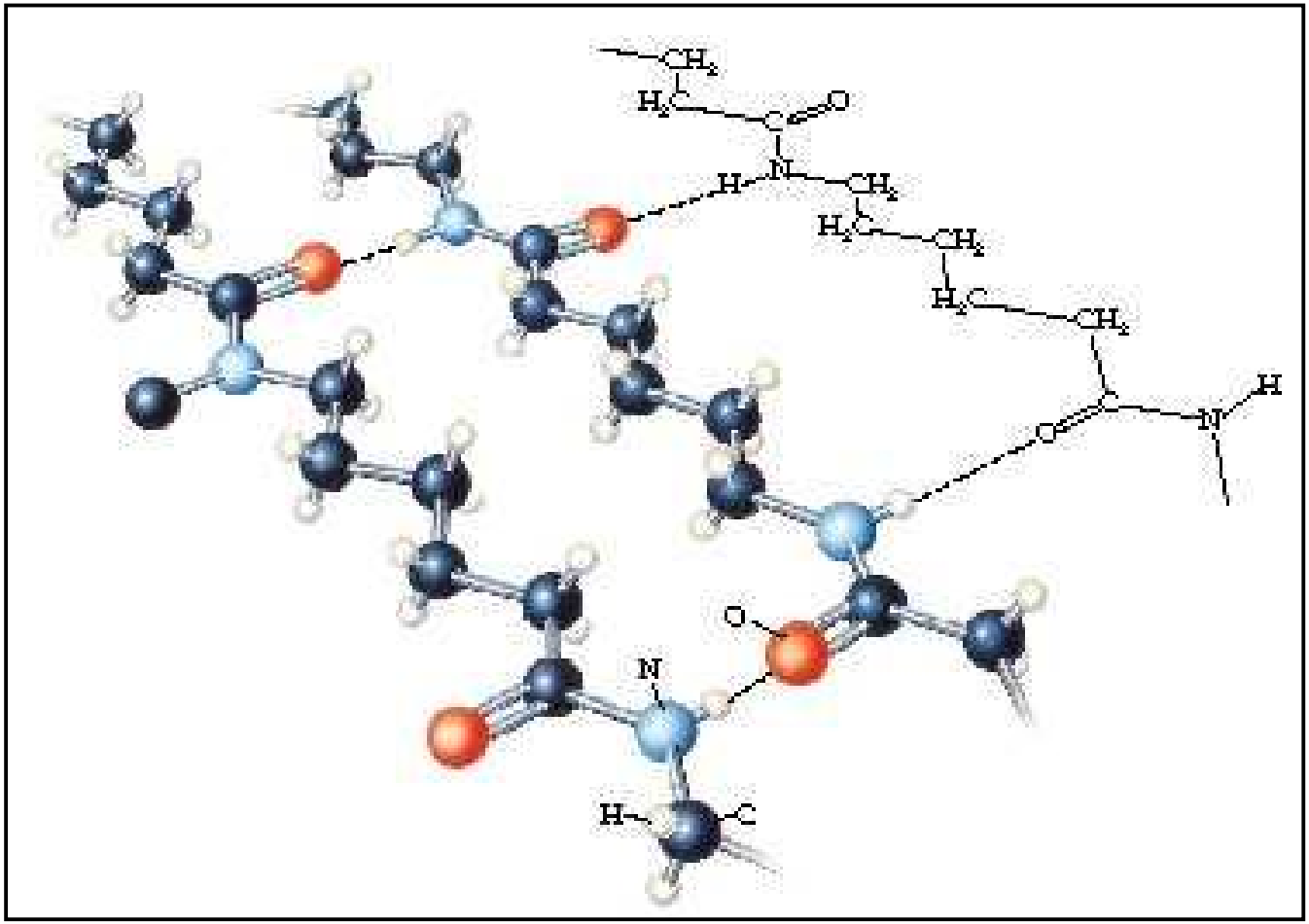


Kink coiling: why it happens?



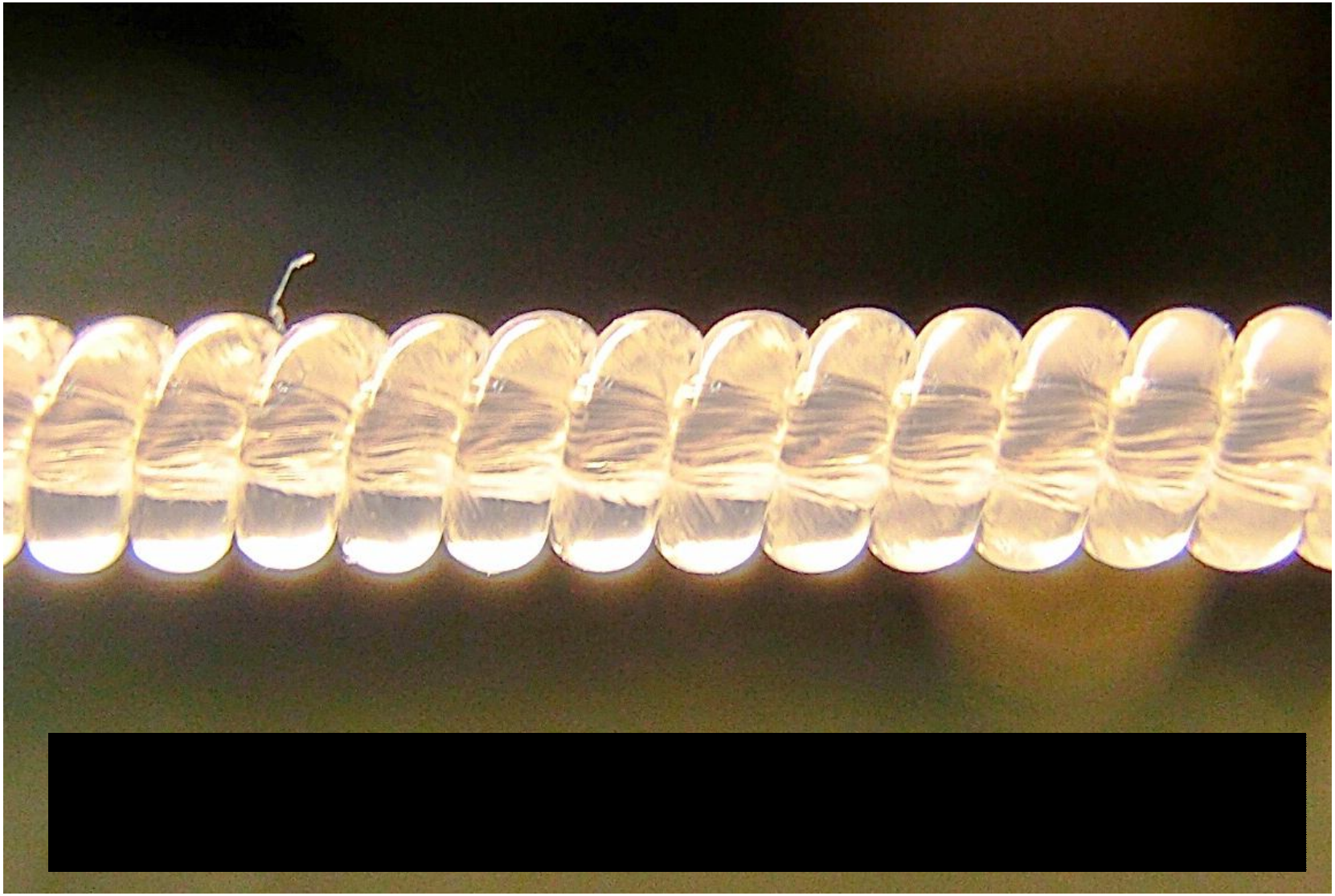
“Rubber motor” IYPT 2014

Why does a released spiral not spin up?



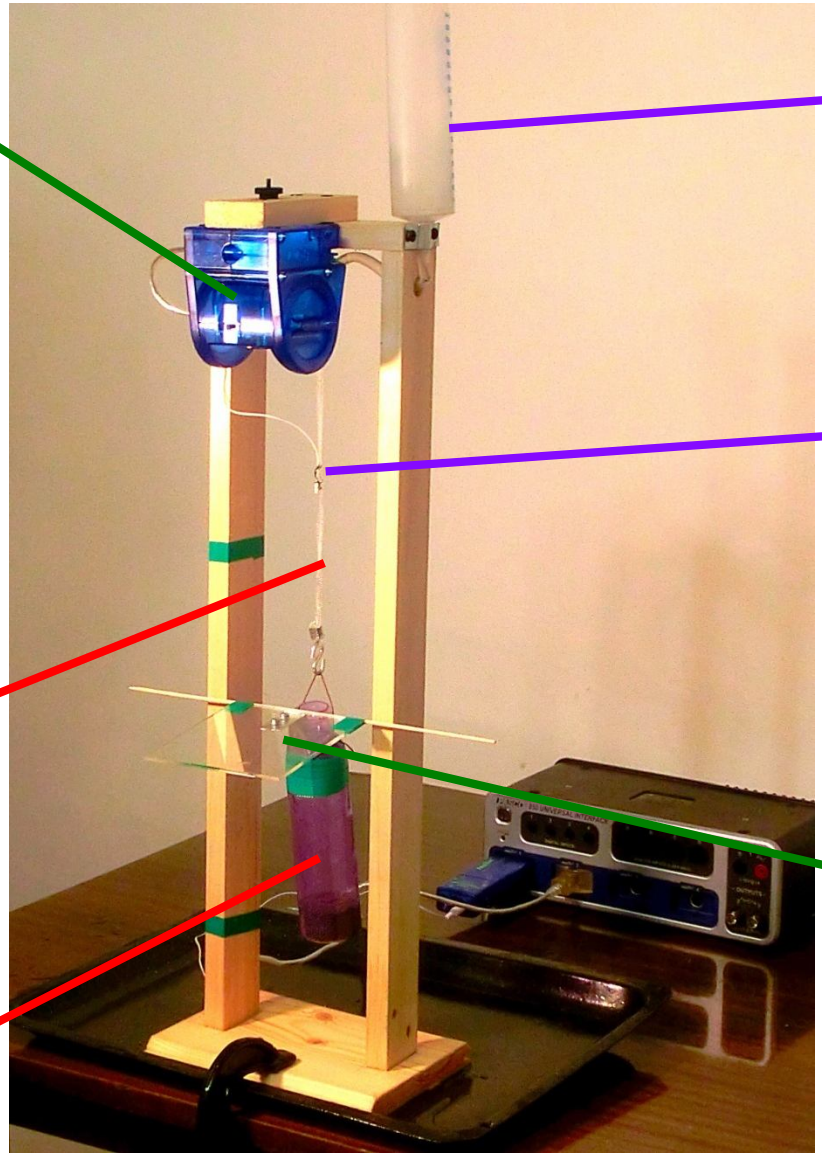
aml.arizona.edu/classes/mse222/1998/nylon66/mse222.htm

Helical muscle



Thermal actuation of artificial muscle

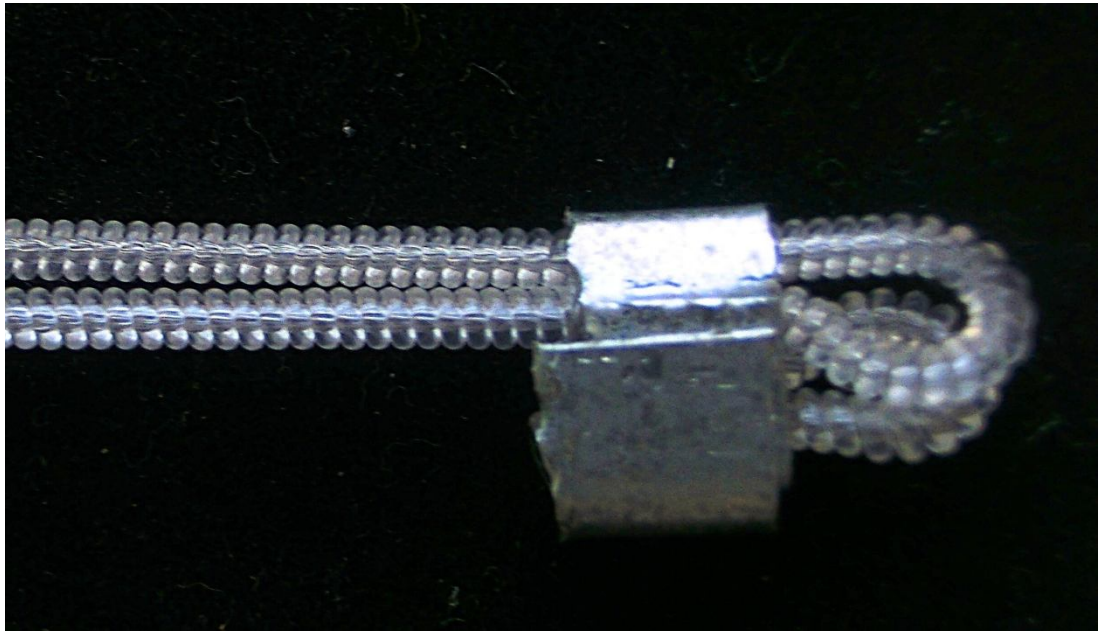
Experimental setup #1



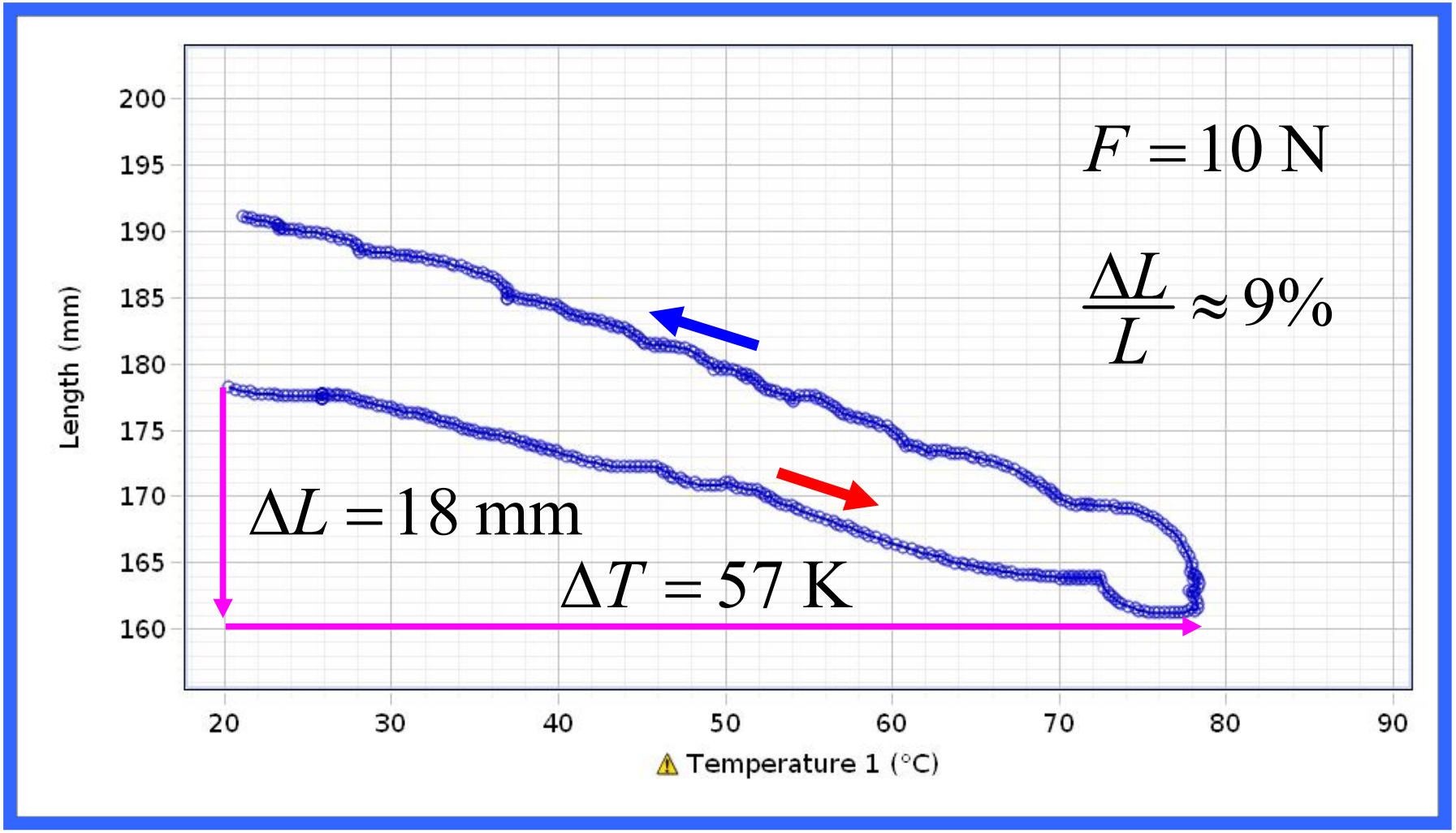
Double spiral

Left spiral

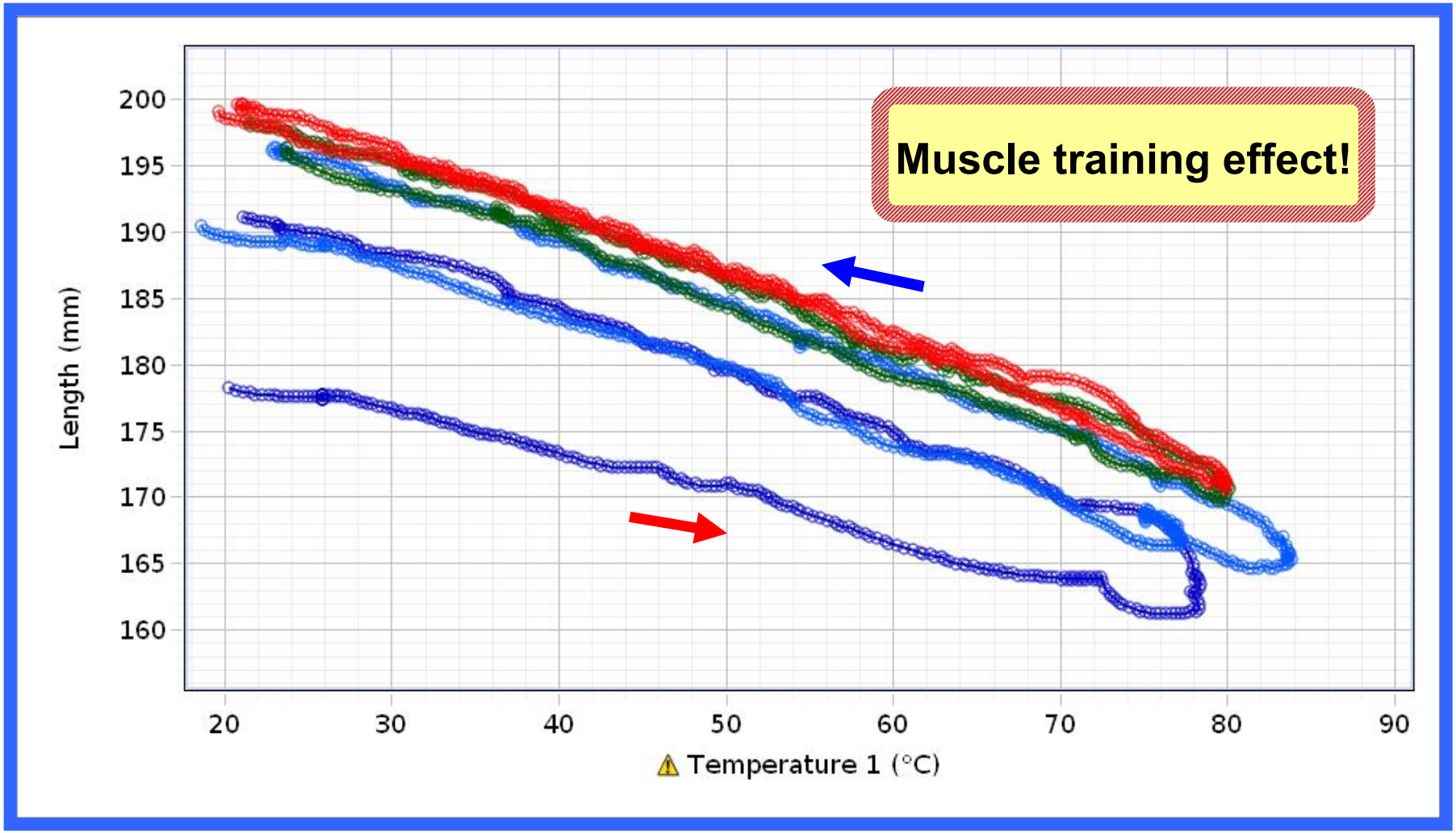
Right spiral



Thermal contraction of spiral muscle

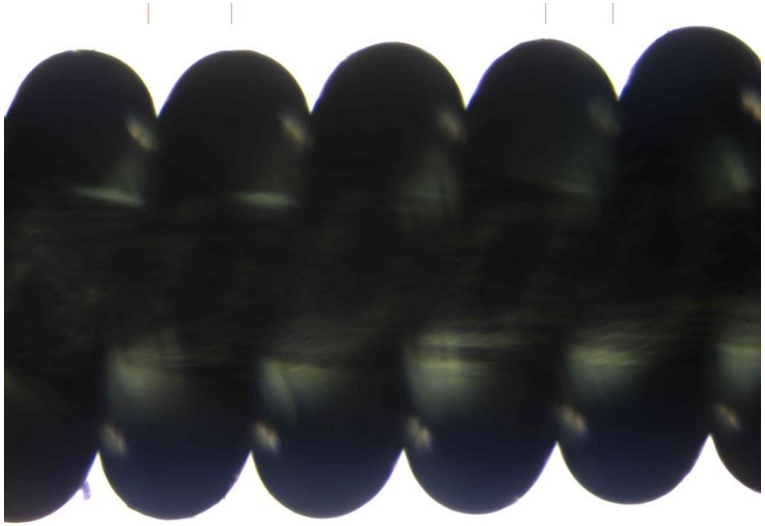


Heating and fixation

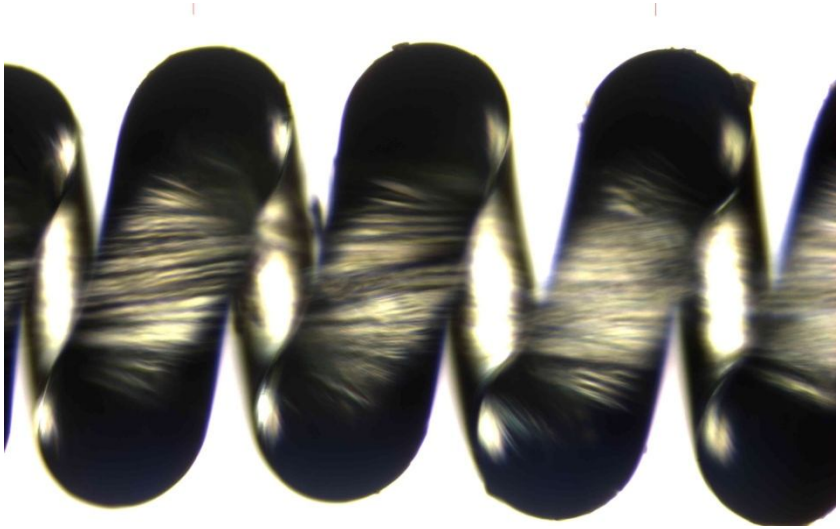


Changes after training

Untrained

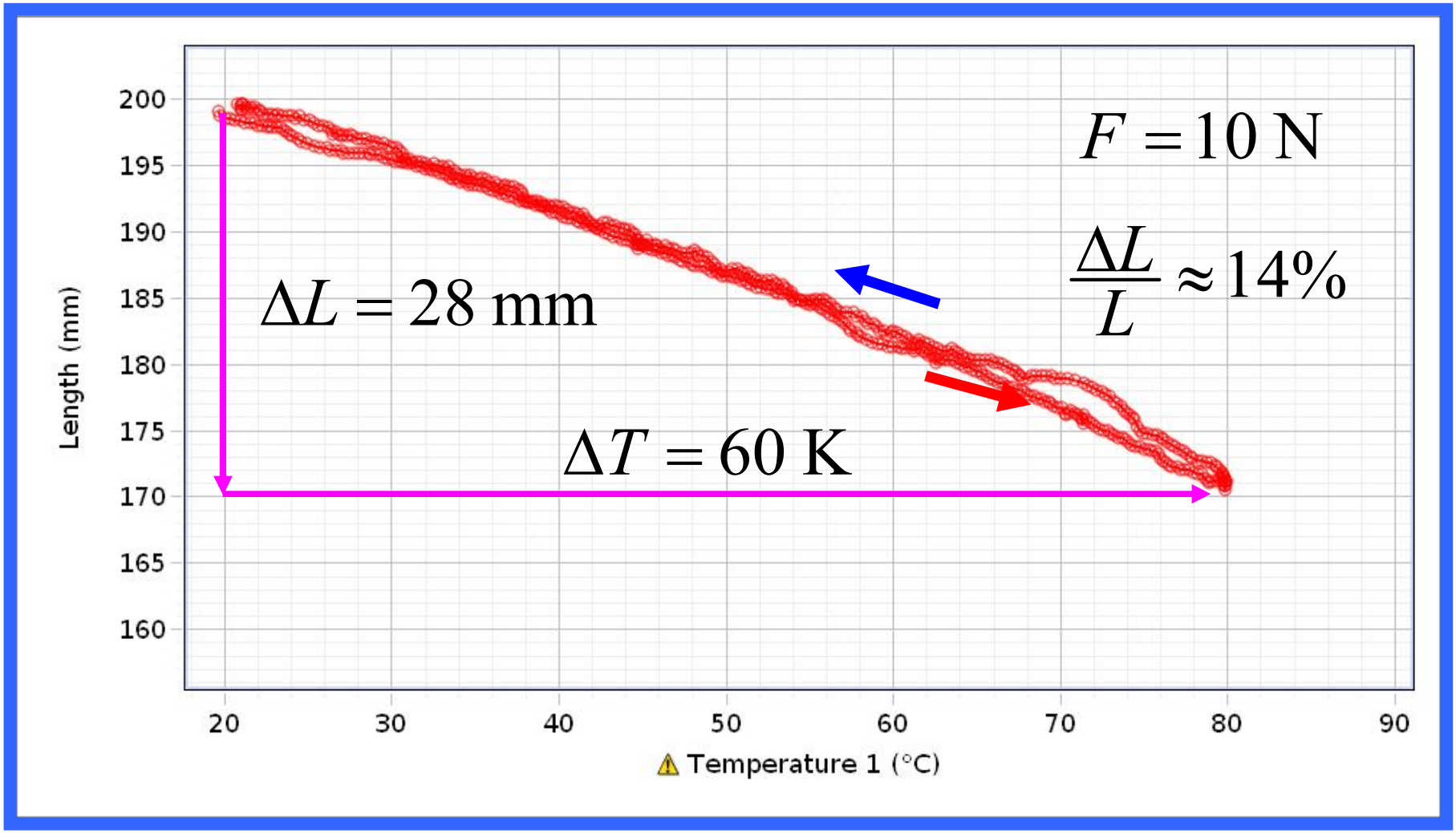


Trained



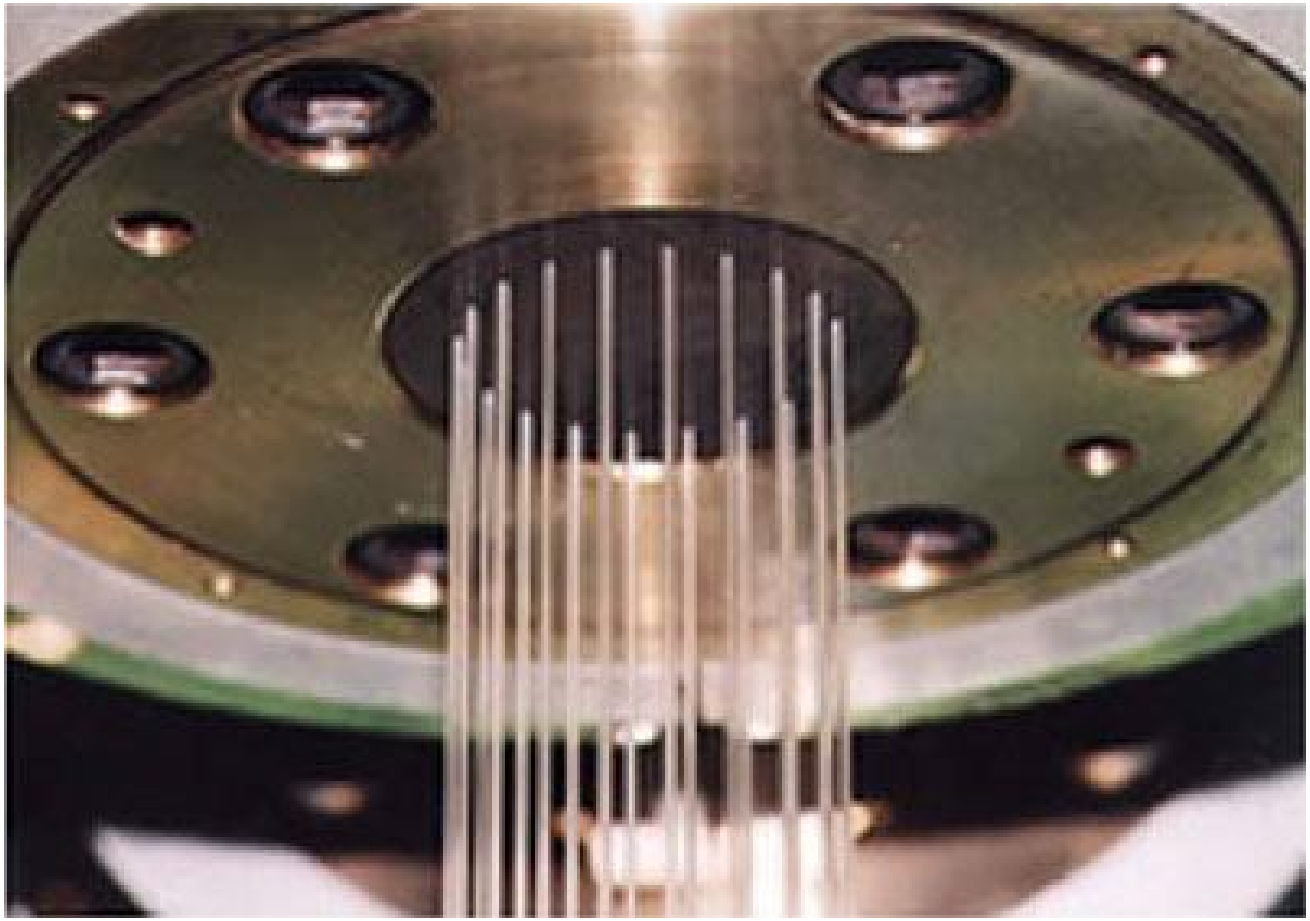
Helical pitch increased after "training"

Heating of a trained spiral muscle



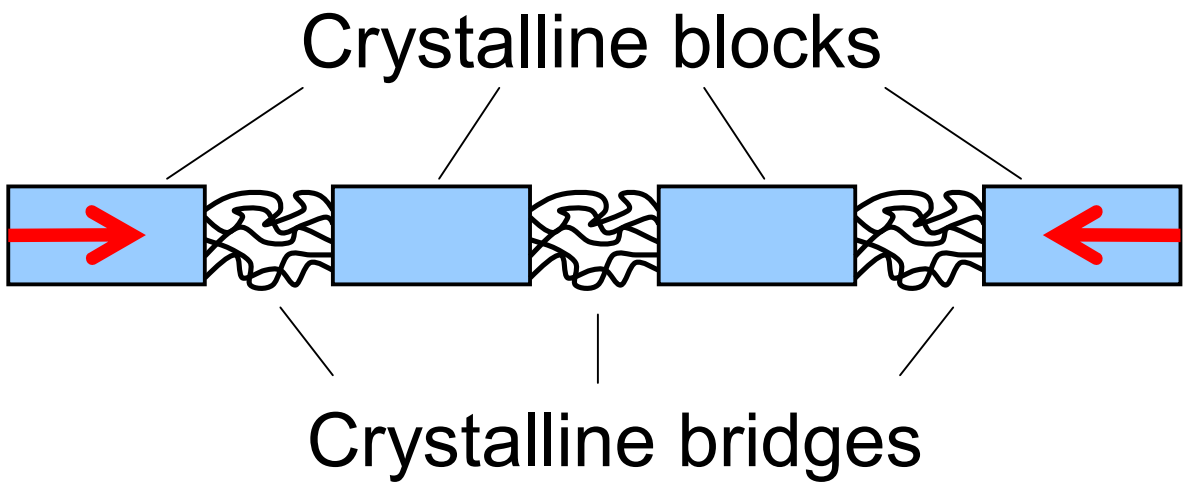
Thermal actuation of fishing line

Fishing line extrusion



Fishing line extruded from the melt through a spinneret.
Polymer molecules are oriented along the fishing lines.

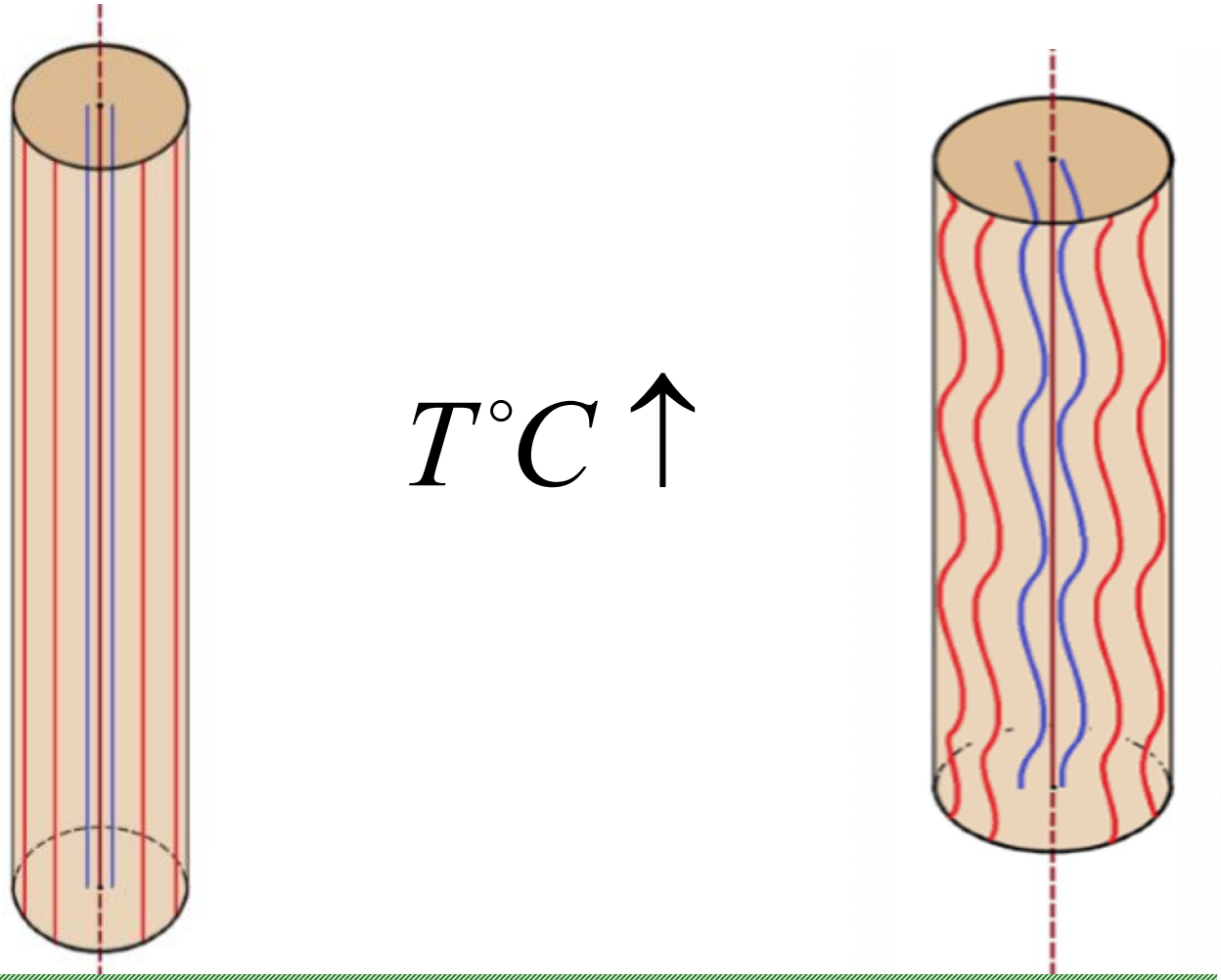
The structure of nylon fiber



The major contribution to the negative thermal expansion in the draw direction comes from the rubber-like elasticity of the extended amorphous tie molecules in the inter-crystalline regions.

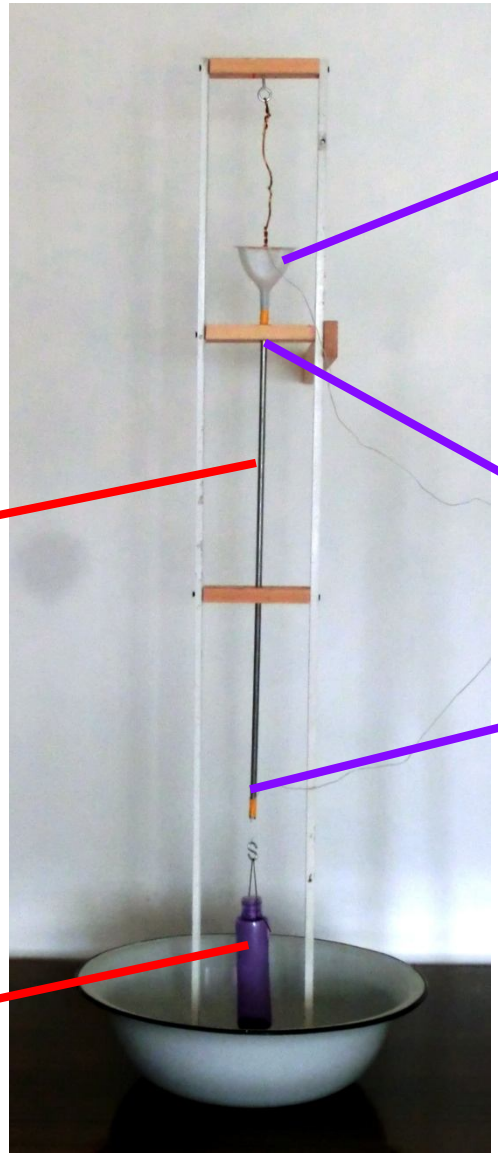
Haines C.S. *et al.* (2014) “Suplementary materials”.

Anisotropy of fishing line under heating



Contraction of the artificial muscle is due to contraction of fishing line.

Experimental setup #2



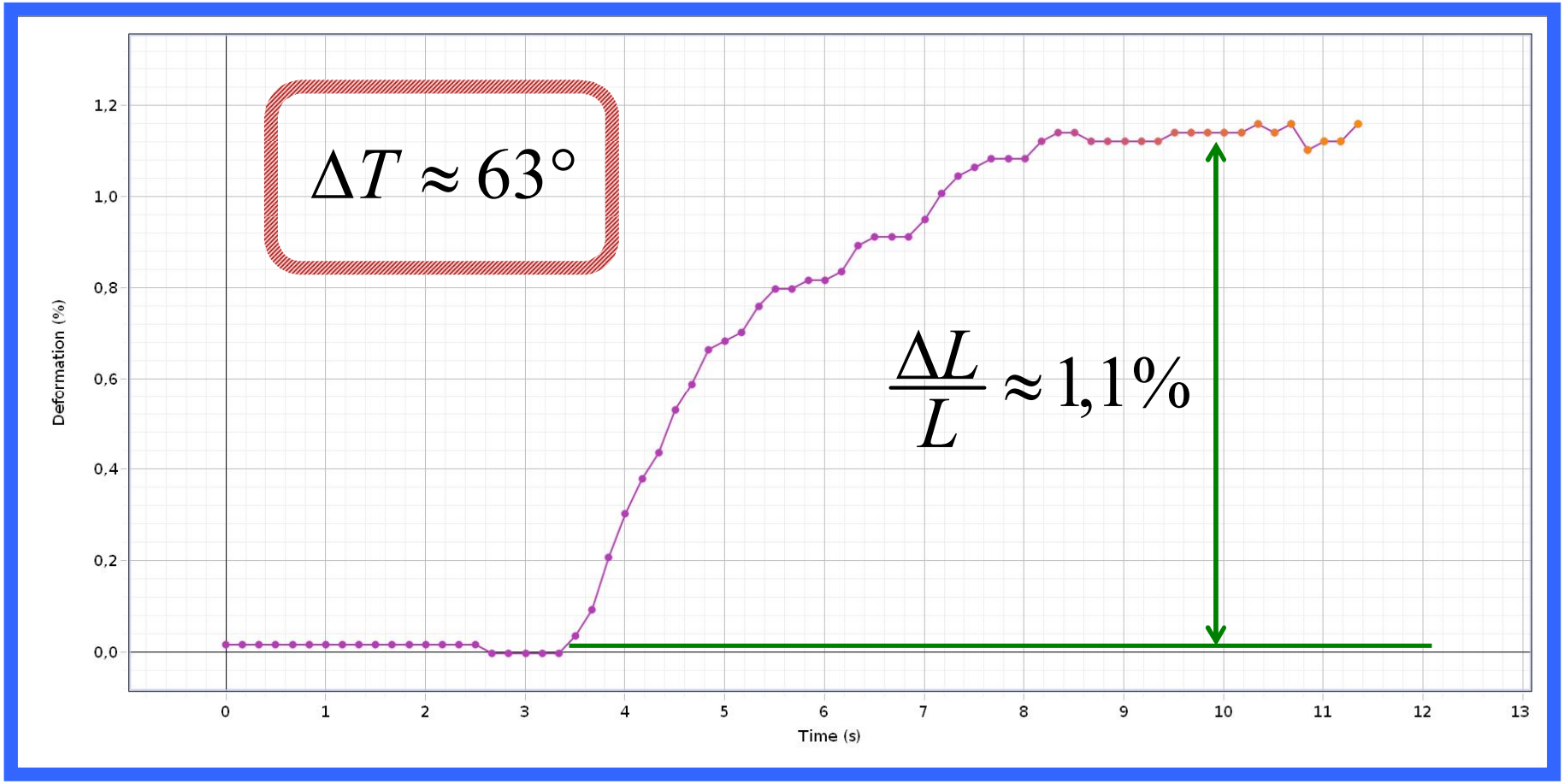
Water supply

Fishing line in the tube

Two temperature sensors

Load

Thermal actuation of non-coiled fiber

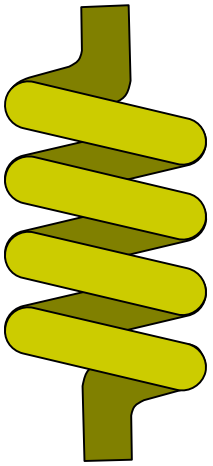


Contraction under load

Fishing line

Artificial muscle

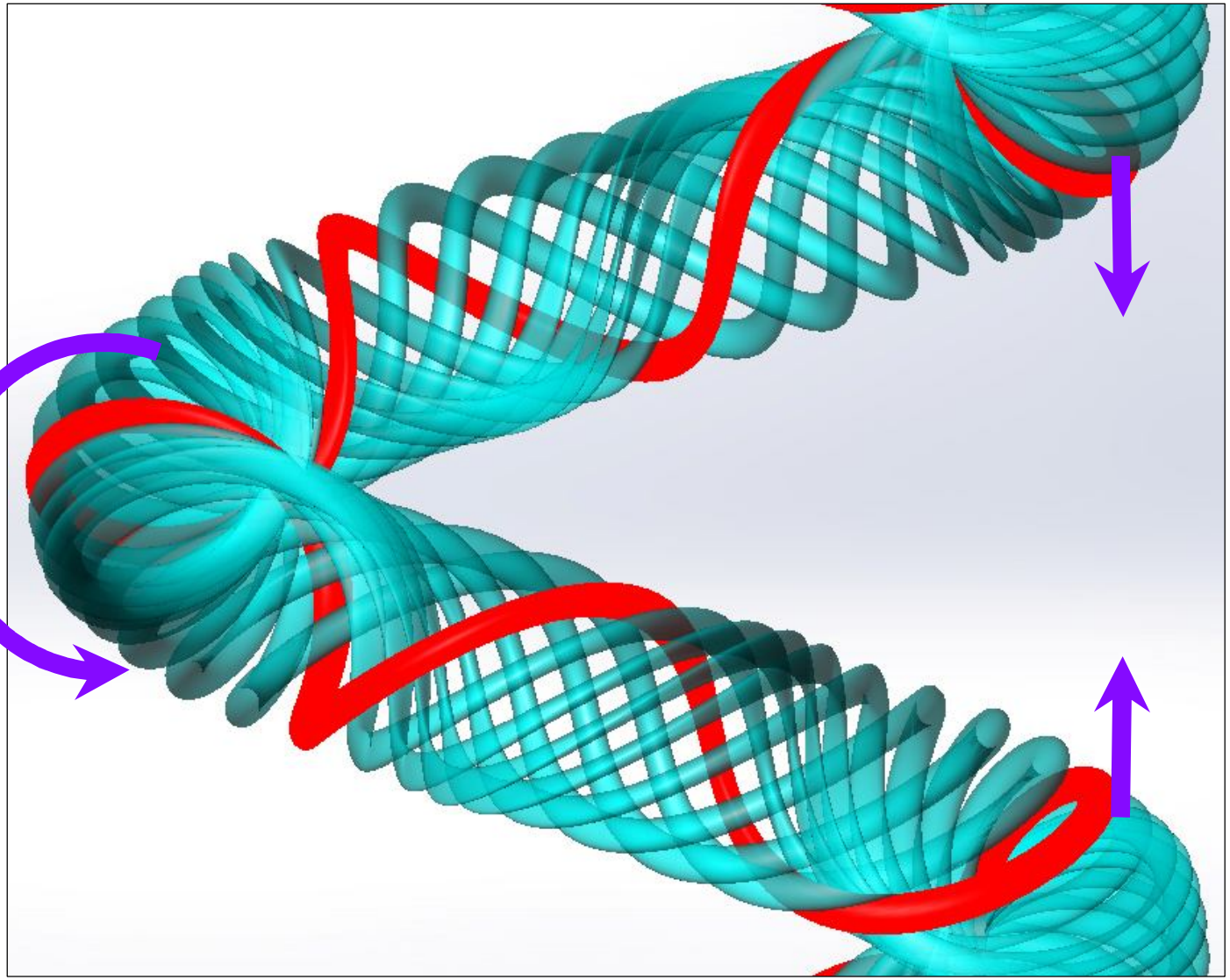
Spiral structure of muscle leads to grater thermal contraction



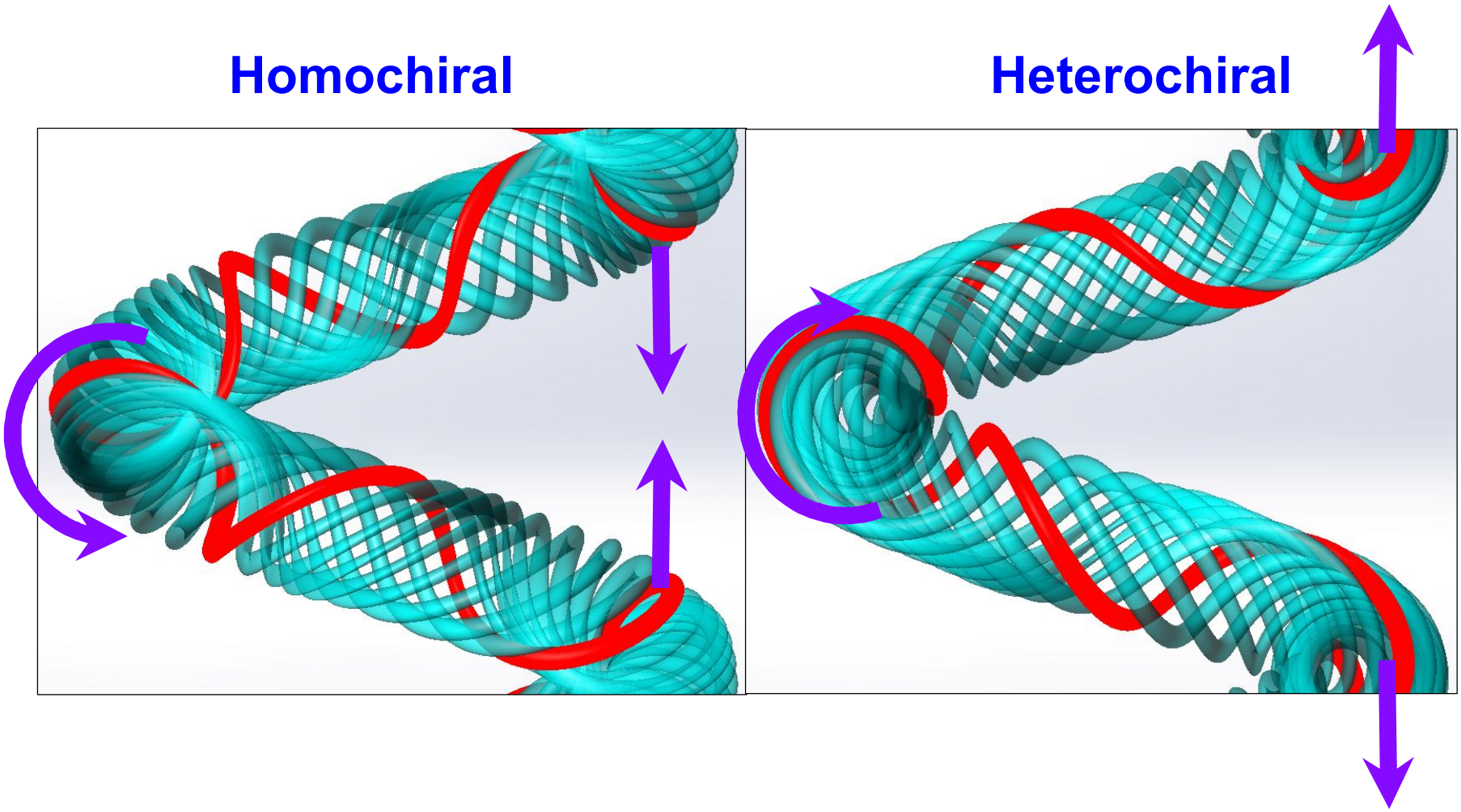
$$\frac{\Delta L}{L} \approx 1{,}1\% \ll \frac{\Delta L}{L} \approx 9\%$$

Muscle's spiral structure

Homochiral structure



Homochiral and heterochiral structure

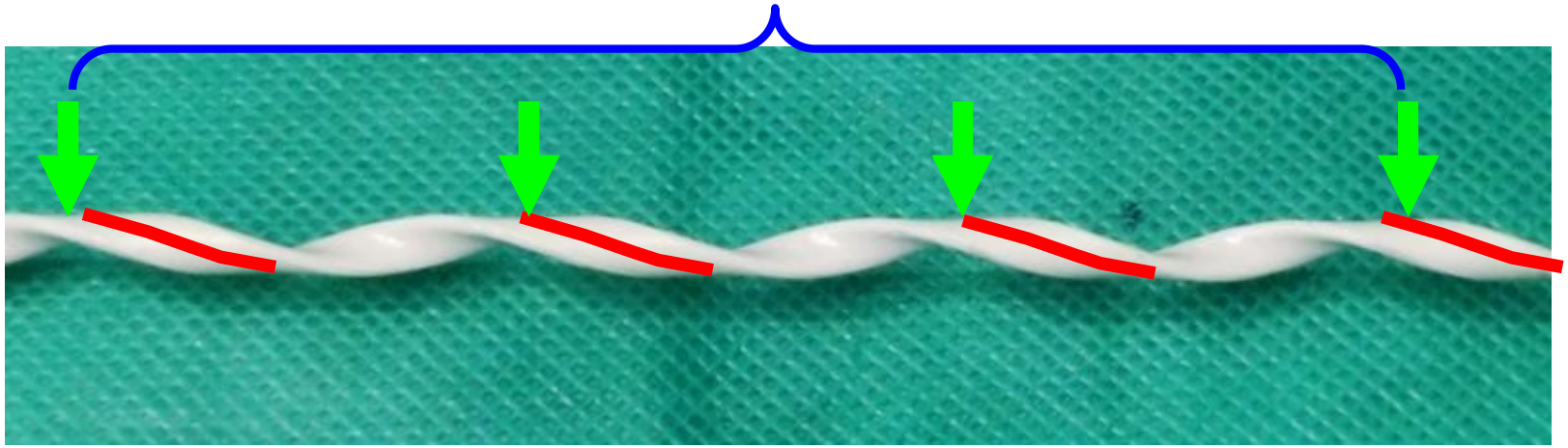


Theoretical prediction for a spiral muscle

Twist number

Twist number shows how many times every fiber in a thread wraps its axis.

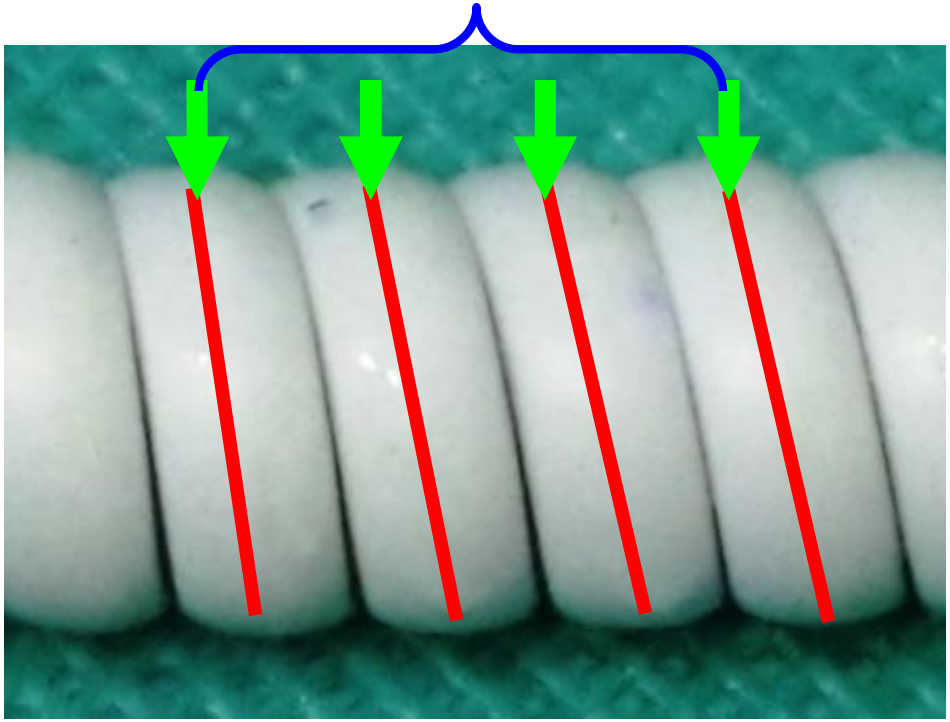
T ≈ 3 **W ≈ 0**



Writhe number

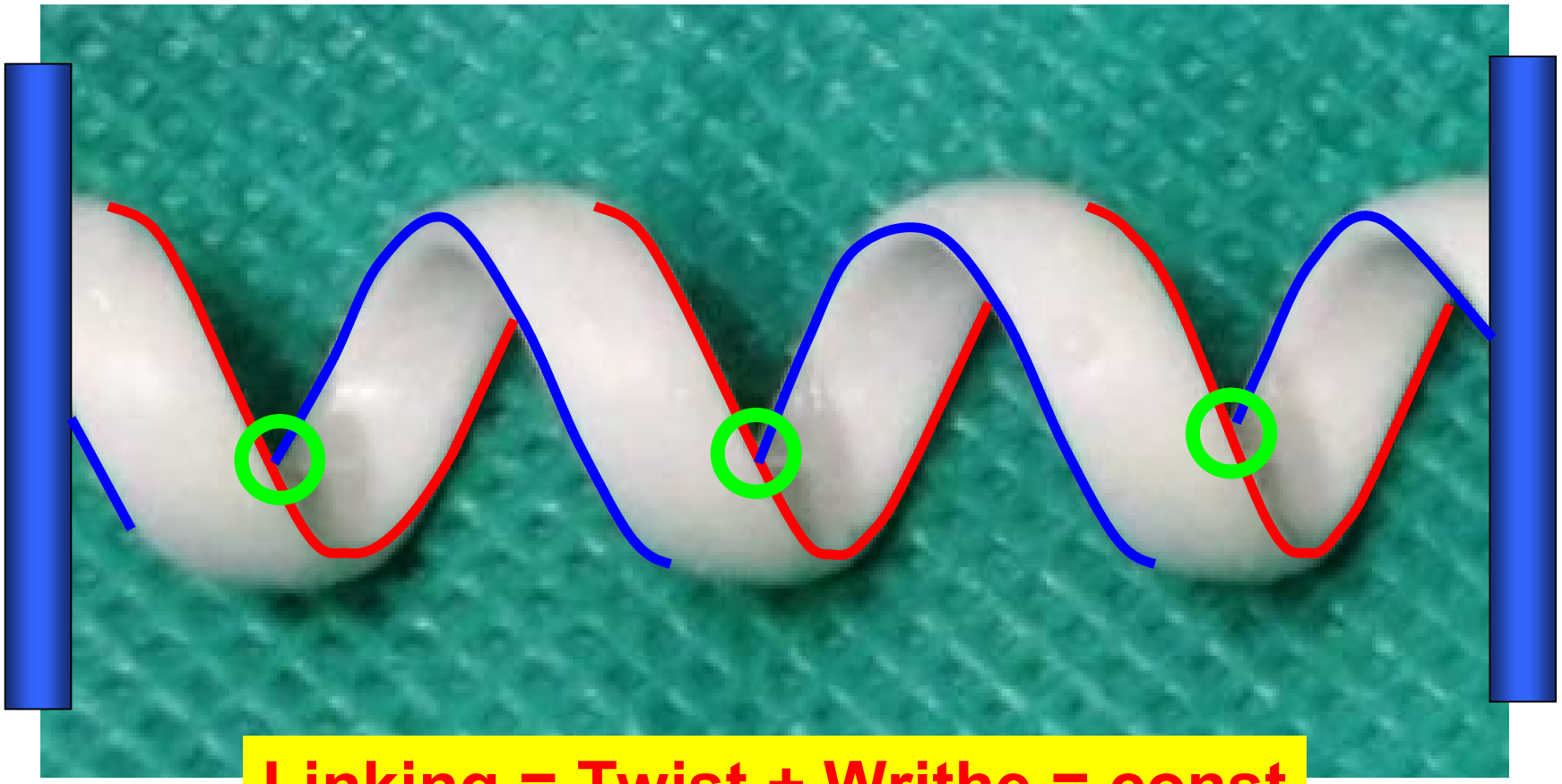
Writhe number shows how many times the thread is coiled about itself in three-dimensional space.

W ≈ 3



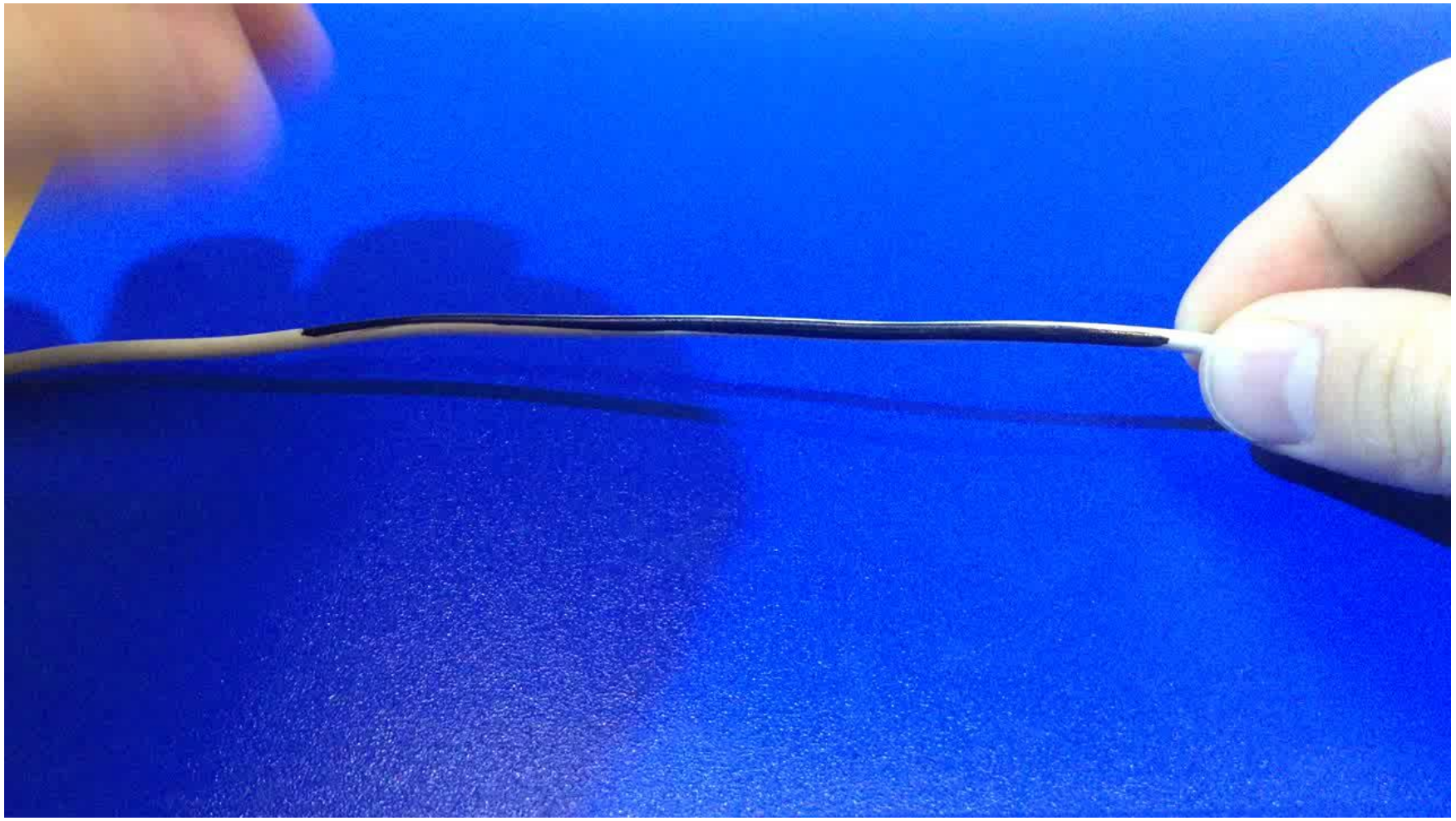
T ≈ 0

Linking number



Linking = Twist + Writhe = const

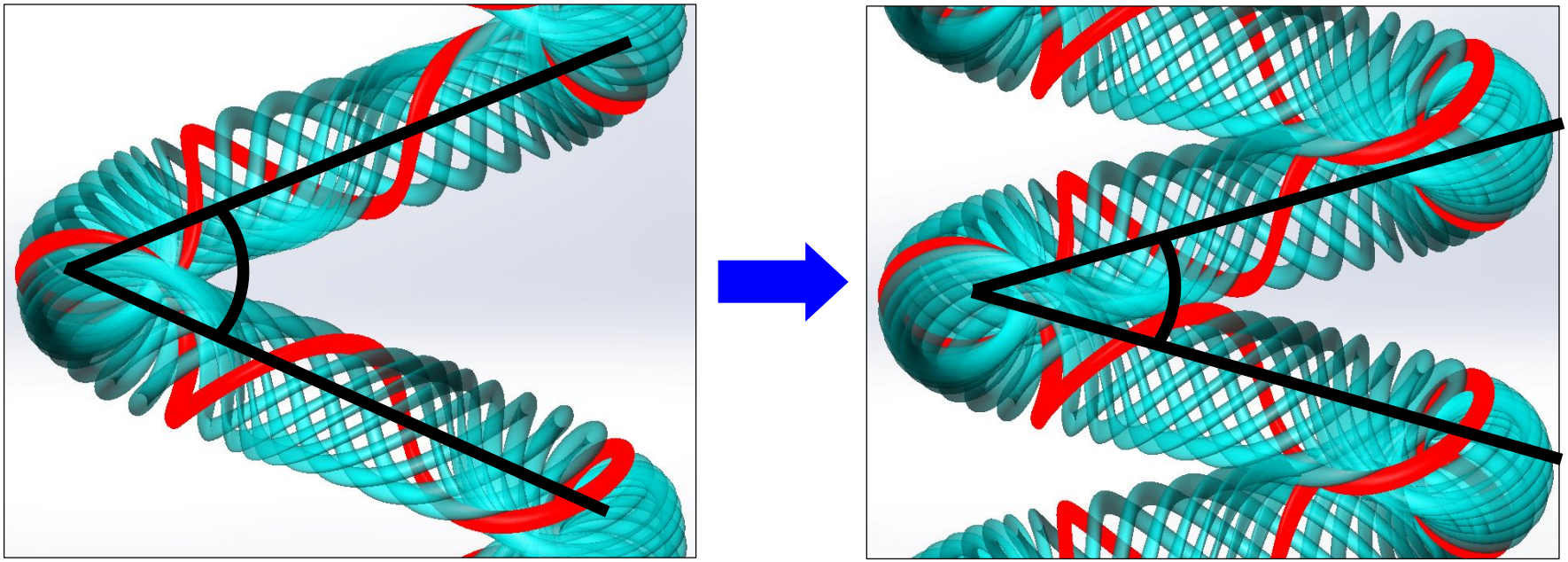
Linking number is a topological invariant



W + T = Lk = const

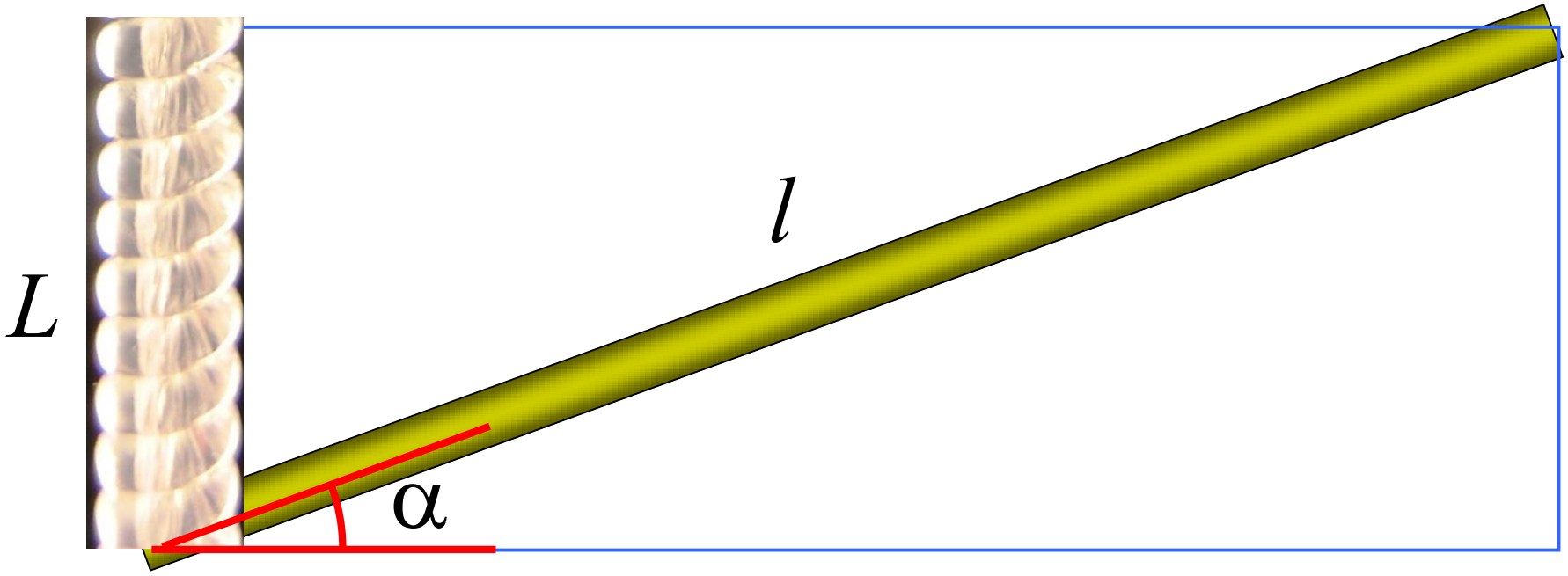
Conservation of linking number

$$Lk = W + T = const$$



$T \downarrow \quad W \uparrow$

Pitch angle of a spiral

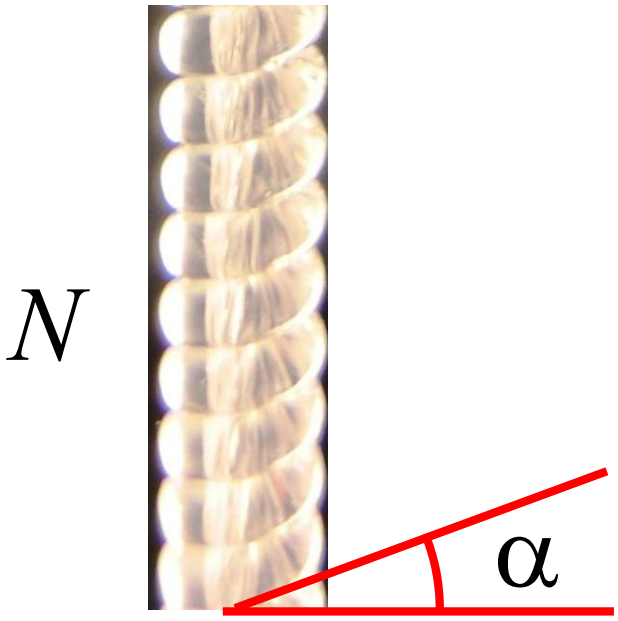


$$L = l \sin\alpha \approx l\alpha$$

Untwisted length

$$\frac{\Delta L}{L} \approx \frac{l}{L} \cdot \Delta\alpha \quad *$$

Writhe and twist numbers



$$W = N(1 - \sin\alpha)$$

$$\Delta\alpha \approx -\frac{\Delta W}{W} = \frac{\Delta T}{W}$$

$$\Delta\alpha \approx \frac{\Delta T}{T} \cdot \frac{T}{W} \quad **$$

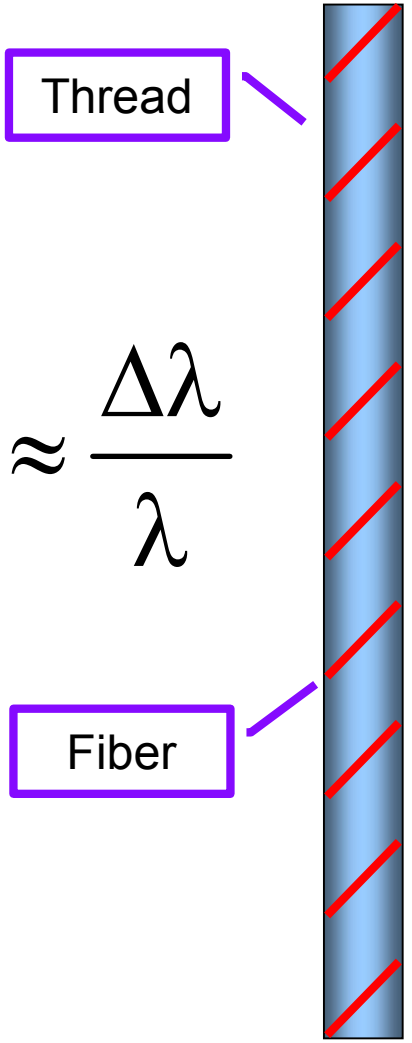
Fuller F.B. (1978) “Decomposition of the linking number of a closed ribbon”.

Ratio of thermal contractions

* $$\frac{\Delta L}{L} \approx \left(\frac{l}{L}\right) \cdot \left(\frac{T}{W}\right) \cdot \frac{\Delta T}{T}$$

** $$\frac{\Delta L}{L} \approx \left(\frac{l}{L}\right) \cdot \left(\frac{T}{W}\right) \cdot \frac{\Delta \lambda}{\lambda}$$

$$\frac{\Delta T}{T} \approx \frac{\Delta \lambda}{\lambda}$$



Definitive parameters

Parameters of a spiral muscle

Length of a fishing line $l = 100$ cm

Length of a spiral $L = 17$ cm

$$\frac{l}{L} = 6$$

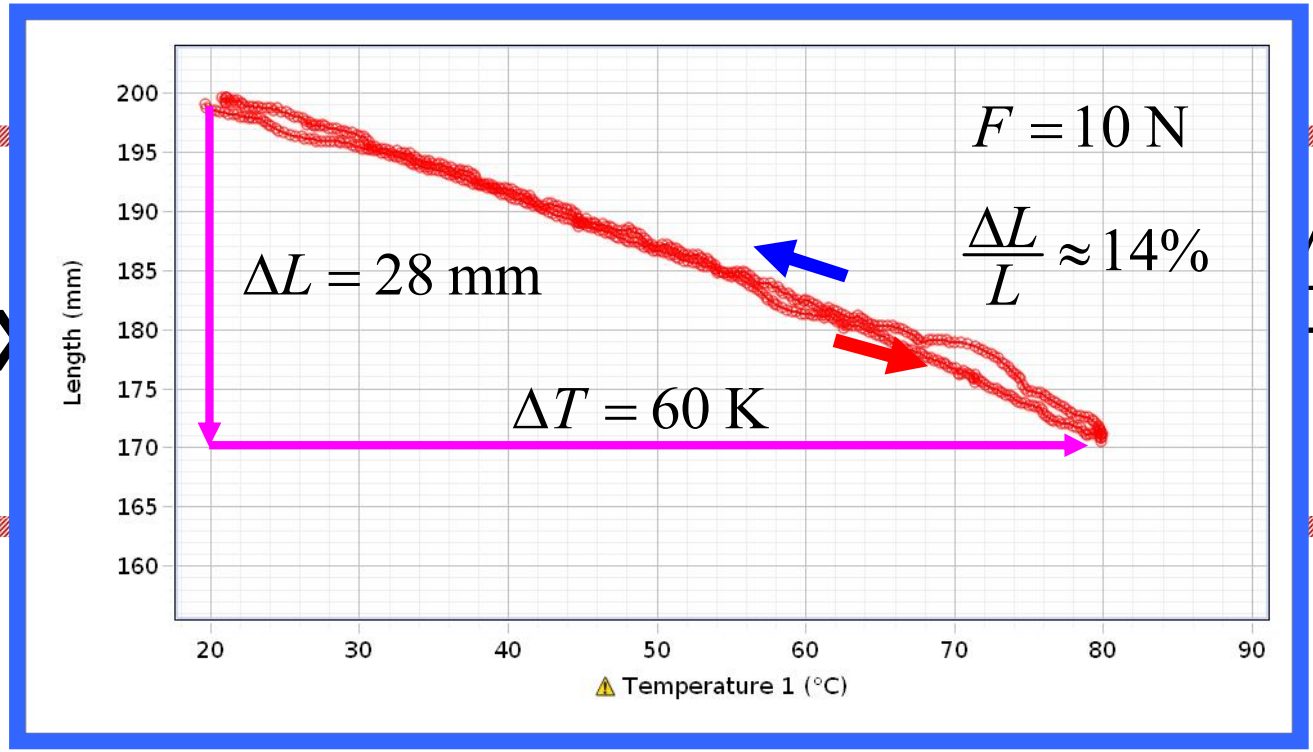
Linking $\mathrm{Lk} = \underbrace{360}_{\text{Twist}} + \underbrace{180}_{\text{Writhe}}$

$$\frac{T}{W} = 2$$

Theory vs. experiment

Theory: $\frac{\Delta L}{L} \approx 12 \cdot \frac{\Delta \lambda}{\lambda}$

Ex $\frac{\Delta \lambda}{\lambda}$



Efficiency

Efficiency

$$\eta = \frac{E_{\text{useful}}}{E_{\text{heat}}}$$

$$E_{\text{useful}} = F \cdot h$$

$$E_{heat} = mc\Delta t$$

Efficiency after training

$$\text{Efficiency} = \frac{E_{\text{useful}}}{E_{\text{heat}}}$$

$$E_{\text{useful}} = F \cdot h = 10\,\text{N} \cdot 18\,\text{mm} = 0{,}18\,\text{J}$$

$$E_{heat} = mc\Delta t = 0.35\text{g} \cdot 1{,}3\,\tfrac{\text{J}}{\text{g}\cdot\text{K}} \cdot 57\text{K} = 26\,\text{J}$$

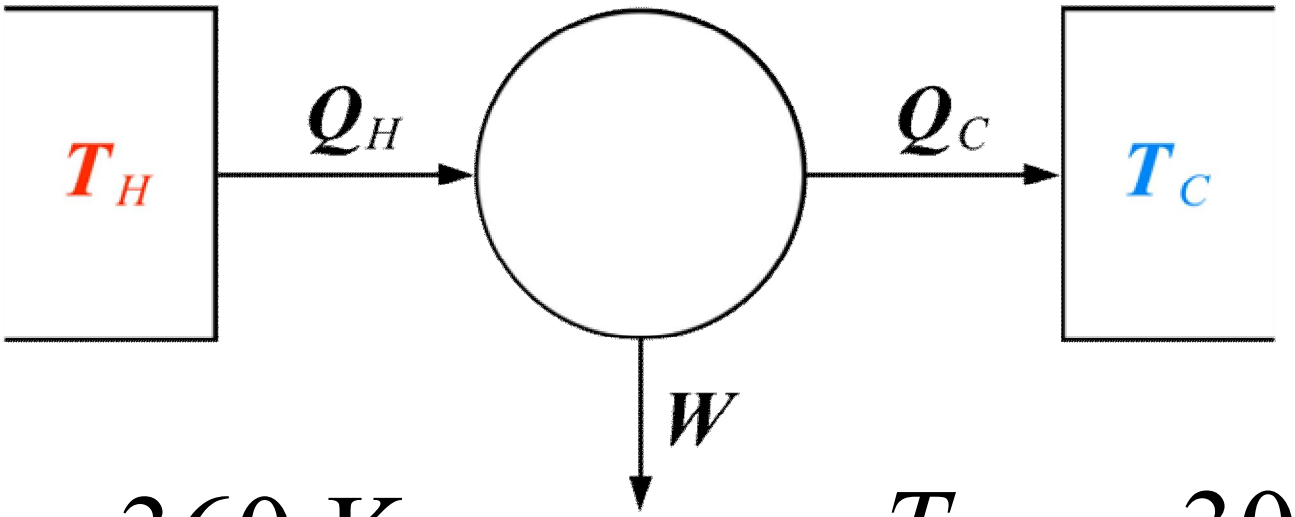
Untrained

$$\eta = \frac{0.18}{26} = 0.69\%$$

Trained

$$\eta = \frac{0.28}{27} = 1\%$$

Efficiency of Carnot heat engine



$$T_{\text{heat}} = 360\ \text{K} \qquad T_{\text{cold}} = 300\ \text{K}$$

$$\eta = 1 - \frac{T_{\text{cold}}}{T_{\text{heat}}} = 0.17$$

$$\eta = \frac{E_{\text{useful}}}{E_{\text{heat}}}$$

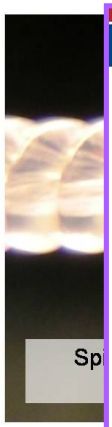
Efficiency

Fishing line	0.025%
Dense non-trained spiral	0.69%
Dense trained spiral	1%
Carnot heat engine	17%

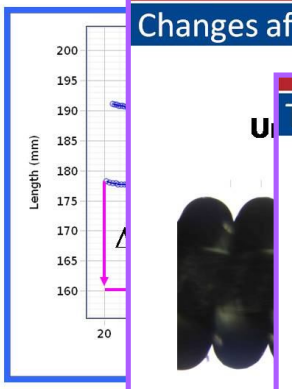
Summary

Conclusions

Helical muscle 10



Thermal contraction of spiral muscle 14



Changes after training 16

The structure of nylon fiber 20

The major
direction
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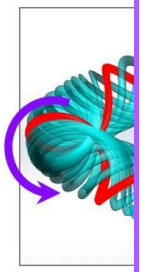
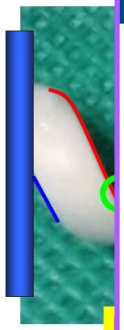
Haines C.S. *et*

Homochiral and heterochiral structure 27



Linking number 31



Ratio of thermal contractions 36

$$* \quad \frac{\Delta L}{L}$$

$$** \quad \frac{\Delta L}{L} \approx$$

Theory vs. experiment 38

Th

Ex

Length (mm)

Efficiency 43

Fishing line	0.025%
Dense non-trained spiral	0.69%
Dense trained spiral	1%
Carnot heat engine	17%

References

- Haines C.S. *et al.* (2014) “Artificial muscles from fishing line and sewing thread”. *Science* **343**, 868–872.
- Choy C.L., Chen F.C., Young K. (1981) “Negative thermal expansion in oriented crystalline polymers”. *J. Polymer Sci.*, **19**, 335–352.

Thank you for your attention!