**Creep**

**Ingredients**
- Driven elastic system, like a magnetic domain wall
- Disordered medium, like a nanostrip
- Nonzero temperature
- Small driving force

**Behaviour**

Slow motion by thermally activated jumps over energy barriers described by $\nu \sim \exp(-C F^{-\alpha}/T)$ with $\nu$ the creep velocity and $\mu$ the creep exponent.

Proven valid for domain walls in extended ferromagnetic thin films with $\mu = 1/4$.

**MuMax simulation details**

- The GPU-accelerated software package MuMaX$^3$ numerically solves the Landau-Lifshitz-Gilbert equation extended with spin transfer torque terms:

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} - |\mathbf{J} \cdot \mathbf{V}| \mathbf{m} + |\mathbf{m} \times |\mathbf{J} \cdot \mathbf{V}| \mathbf{m}.$$

- To take thermal effects into account, the effective field $\mathbf{H}_{\text{eff}}$ is extended with a stochastic term $\mathbf{H}_{\text{st}}$ with properties:

$$(\mathbf{H}_{\text{st}})_{0} = 0, \quad (\mathbf{H}_{\text{st}}(t))_{0}(t') = q \mathbf{B}_{0}(t-t') \delta(t'), \quad q = \frac{2a T_{0} \mathbf{m}_{0}}{M_{s} T_{0}}.$$ 

- The system under study is a transversal domain wall in an infinitely long Py nanostrip with cross-sectional dimensions of $10 \times 100 \text{nm}^2$, simulated in a moving window with length 800 nm, centered around the DW.

- Disorder is included as a Voronoi tessellation, representing grains with an average size of 10 nm and with 20% exchange stiffness reduction at the edges of the material grains.

**Problem statement**

- In contrast to wide nanostrips, the creep scaling law fails to describe the domain wall motion in narrow geometries.
- These smaller geometries become increasingly important in nanotechnology.

**Equation of motion**

Starting from a generalised 1D-model, we derived an equation which describes the motion of a magnetic DW, driven by spin-polarised currents and/or applied fields along a nanostrip with material imperfections at finite temperatures.

$$\frac{d\mathbf{v}}{dt} = \mathbf{a} \cdot \mathbf{v} + \frac{L_{0} \mathbf{m}(t) \cdot \mathbf{v}}{L_{0} \mathbf{m}(t) \cdot \mathbf{v}} + \frac{\mathbf{m} \cdot \mathbf{V}}{\mathbf{m} \cdot \mathbf{V}} + \mathbf{E}_{\text{ext}}.$$ 


**High-friction limit**

In the high-friction limit, the mass of the domain wall can be neglected and the equation of motion reduces to

$$\Gamma \mathbf{v} = -\mathbf{a} \cdot \mathbf{v} + \frac{L_{0} \mathbf{m}(t) \cdot \mathbf{v}}{L_{0} \mathbf{m}(t) \cdot \mathbf{v}} + \frac{\mathbf{m} \cdot \mathbf{V}}{\mathbf{m} \cdot \mathbf{V}} + \mathbf{E}_{\text{ext}} + 2 \mu_{s} M_{s} H_{\text{ext}},$$

(1)

In this case, an analytical solution for the domain wall velocity at small driving forces exists and is given by

$$\mathbf{v} = -\mathbf{E} + 2 \mu_{s} M_{s} H_{\text{ext}} \exp \left( \frac{-\mathbf{E}^2}{4 \mu_{s} M_{s} H_{\text{ext}}} \right).$$

(2)

again displaying a linear relationship between the velocity and the driving force.

**Conclusion**

- We derived an equation of motion for magnetic domain walls driven along a nanostrip with material imperfections at finite temperature, and validated it against experimental data and full micromagnetic simulations.
- We found that the creep velocity displays a linear dependence on the driving force in narrow nanostrips, contrary to the highly non-linear creep found in larger geometries.

**Results**

- Each data point shows the average velocity over five full micromagnetic simulations and allow to validate the equation of motion (full black lines).
- After validation, we use the equation of motion to investigate current regimes which are inaccessible to full micromagnetic simulations.
- In the low current regime, a linear relation is found between the velocity and the driving force.

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