# Micromagnetics and Skyrmions

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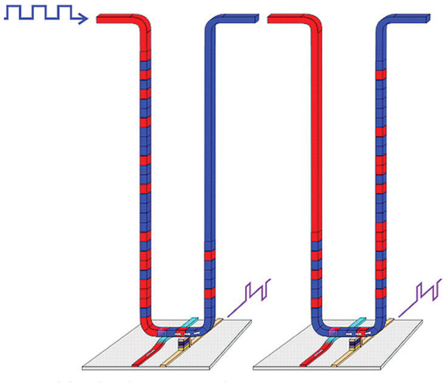
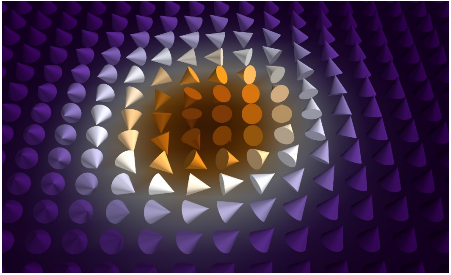
# Racetrack Memory (Parkin et al. 2008)

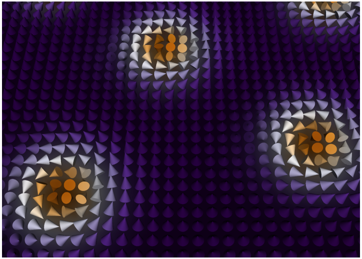
- Compromises
- Magnetic domains represent bits, driven by bursts of spin-polarised current (spin-momentum transfer).
- "3D" structure, for compactness
- Permalloy (it's a ferromagnet)



# Skyrmions

- A vortex-like defect in the magnetic moment field.
- Have position, and interactions with other magnetic structures.
- Phase transitions
- Detected in helimagnets and multilayer ferromagnets.





# For Racetrack Memory

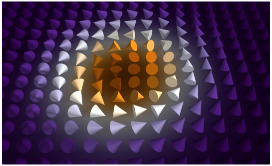
Skyrmions can:

– be much smaller than domain walls (50nm vs atom spacings). **Better storage density!**

– be driven by much weaker spin-polarised currents under light pinning ($10^{12}\mathrm{Am}^{-2}$ vs $10^{6}\mathrm{Am}^{-2}$ (very roughly)). **Less power required to shift!**

The catch?

– Stability (not insurmountable, just unknown).



– Smaller material "parameter space".

# Skyrmion Logic (Zhang et al. 2015)

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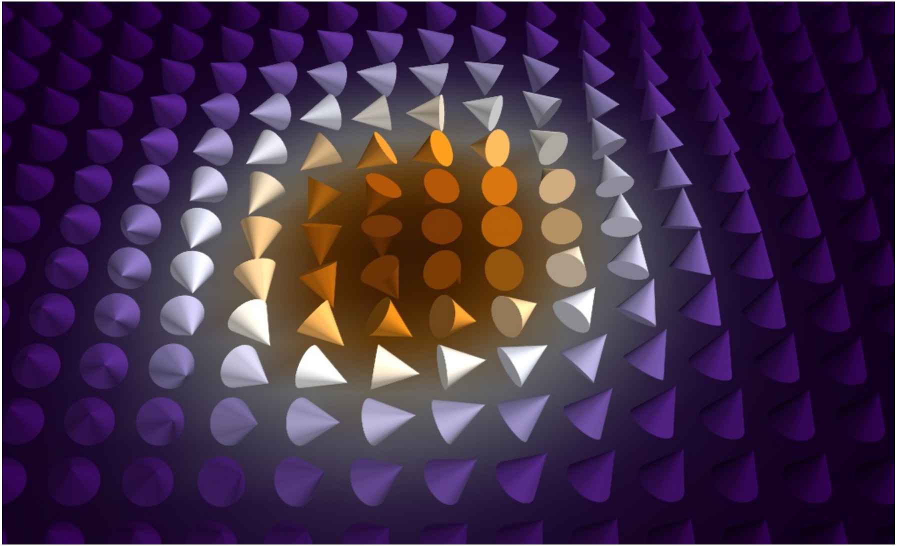
– 1ns transfer time.

– All simulated, but a popular research area today.

# Micromagnetic Model: The Magnetisation

- The motion of an atom's electron creates a magnetic dipole.
- Sum over all electrons, and instrinsic moments, to get an atom's magnetic moment.
- Model these magnetic moments as vector field $\hat{\mathbf{m}}(\mathbf{x})$ (normalised).
- Continuum assumption

$$\hat{\mathbf{m}}$$



# Micromagnetic Model: Exchange Energies

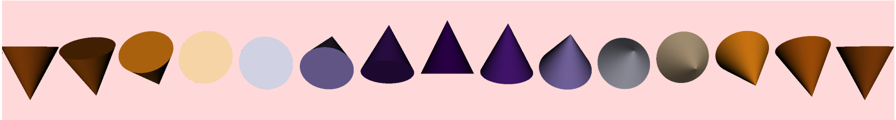
- Isotropic exchange energy favours aligned neighbouring moments:

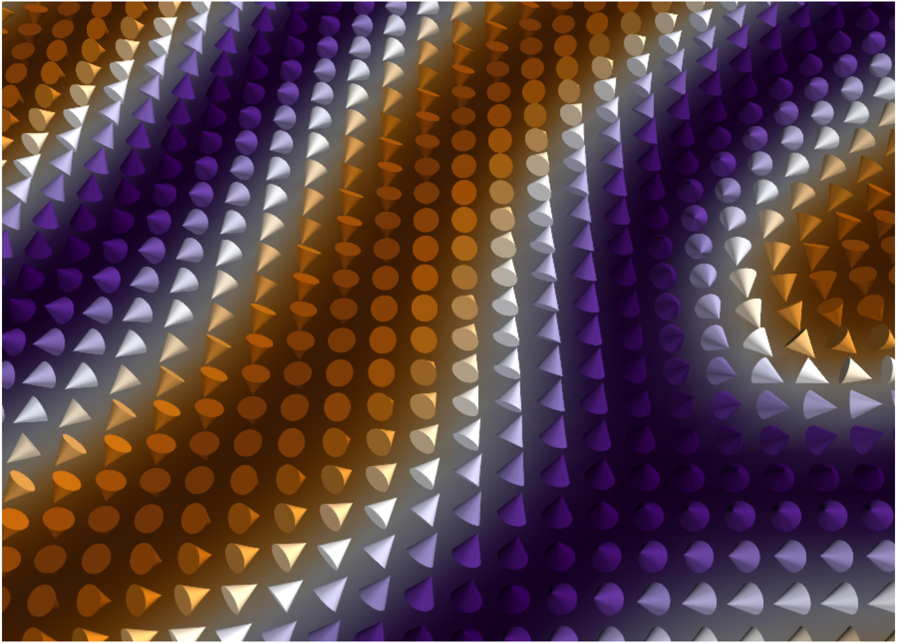
$$w_{\mathrm{exch}}(\hat{\mathbf{m}}) = A\left(||\nabla \mathbf{m}_x||^2 + ||\nabla \mathbf{m}_y||^2 + ||\nabla \mathbf{m}_z||^2\right).$$

- Dzyaloshinskii-Moriya exchange favours perpendicular neighbouring moments (from helimagnets/multilayers):

$$w_{\mathrm{dmi}}(\hat{\mathbf{m}}) = D\hat{\mathbf{m}} \cdot (\nabla \times \hat{\mathbf{m}}).$$

- The compromise forms a helix:

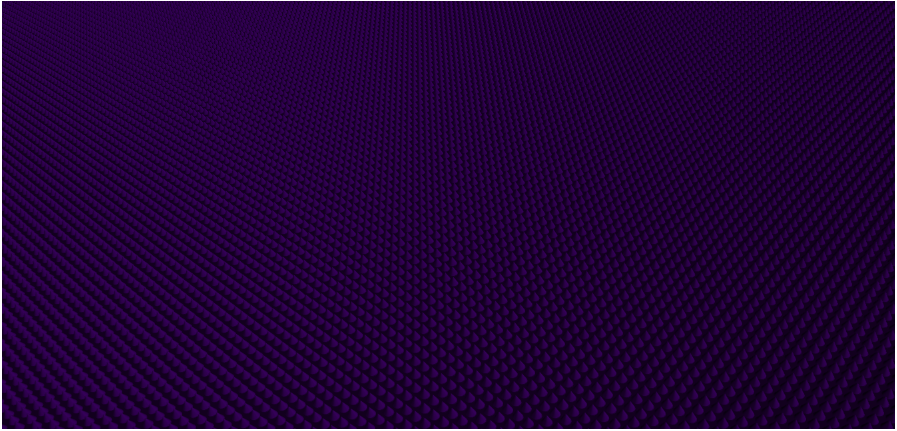




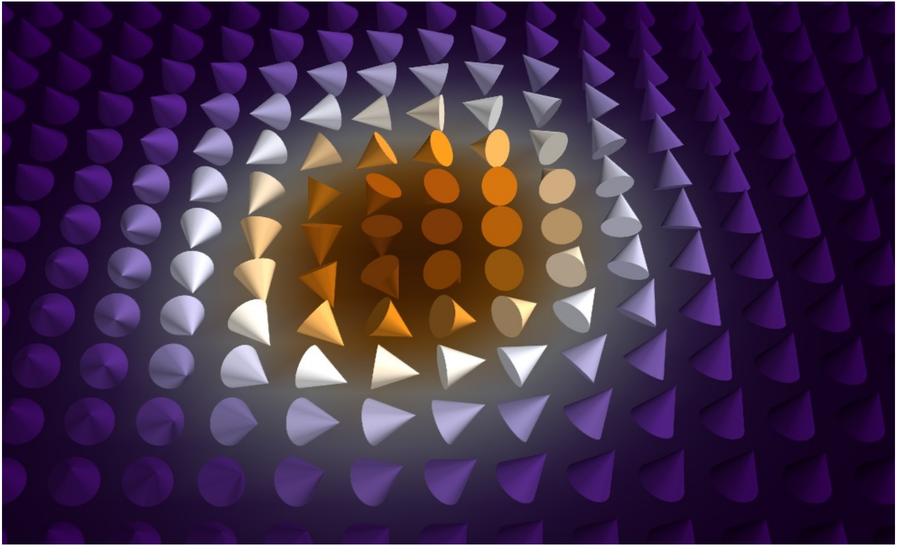
# Micromagnetic Model: Zeeman

– What happens when you put a strong magnet next to it...

$$w_{\mathrm{zeeman}}(\hat{\mathbf{m}}) = -\mu_0 M_{\mathrm{S}} \hat{\mathbf{m}} \cdot \mathbf{H}$$



# But when everything is just right...



# Other Energies

- Various anisotropies:
  - Magnetocrystalline (electron orbital positioning, doping)
  - Magnetostriction (straining)
- Demagnetisation (think bar magnets, long-range)

$$w_{\mathrm{demag}}(\hat{\mathbf{m}}) = -\frac{\mu_0 M_{\mathrm{S}}}{2} \left(\mathbf{H}_{\mathrm{N}} \cdot \hat{\mathbf{m}}\right), \quad \mathbf{H}_{\mathrm{N}} = -\nabla U,$$

$$U(\mathbf{x}) = \frac{M_{\mathrm{S}}}{4\pi} \left( \int_S \frac{\hat{\mathbf{n}} \cdot \hat{\mathbf{m}}(\mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|} \, \mathrm{d}S' - \int_V \frac{\nabla' \cdot \hat{\mathbf{m}}(\mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|} \, \mathrm{d}V' \right)$$

# Then you need your supercomputer...

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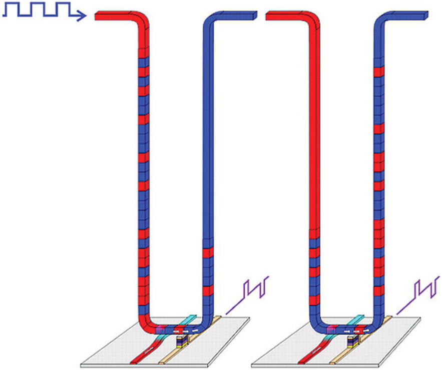
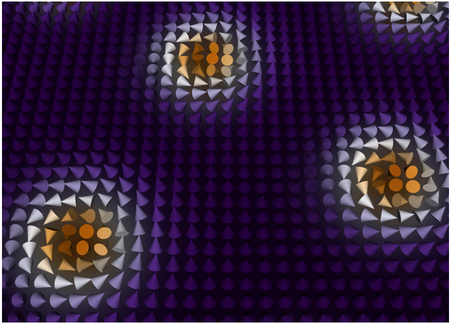
- Event-based computing?

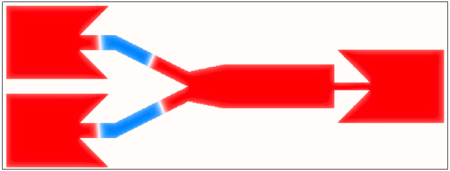
- It's an initial value problem

**...but it's a cool research field,**

**and it might just be useful.**







# Energy-Driven Dynamics

- Landau-Lifshitz (1939) -Gilbert (2004) phenomological dynamics
- Energies combine to create an effective magnetic field:

$$\mathbf{H}_{\text{eff}}(\mathbf{x}_0, t_0) = -\frac{1}{\mu_0 M_{\text{S}}} \frac{\delta W[\hat{\mathbf{m}}(\mathbf{x}, t)]}{\delta \hat{\mathbf{m}}(\mathbf{x}_0, t_0)}$$

- This effective field perturbs the magnetic moment field:

$$\frac{\partial \hat{\mathbf{m}}}{\partial t} = \underbrace{-|\gamma| \hat{\mathbf{m}} \times \mathbf{H}_{\text{eff}}}_{\text{precession}} + \underbrace{\alpha \hat{\mathbf{m}} \times \frac{\partial \hat{\mathbf{m}}}{\partial t}}_{\text{damping}}$$

- It's an initial-value problem!

# Challenges

- Material and geometry selection still a bit up in the air, but people are gravitating towards multilayer materials.

- Pinning mechanisms (notches, holes, material boundaries)

- Behaviour is difficult to verify experimentally (equipment and expertise). Everything I've said here has been observed experimentally.

- Many carriers under consideration (spin waves and magnons, domain walls, merons, antiskyrmions).