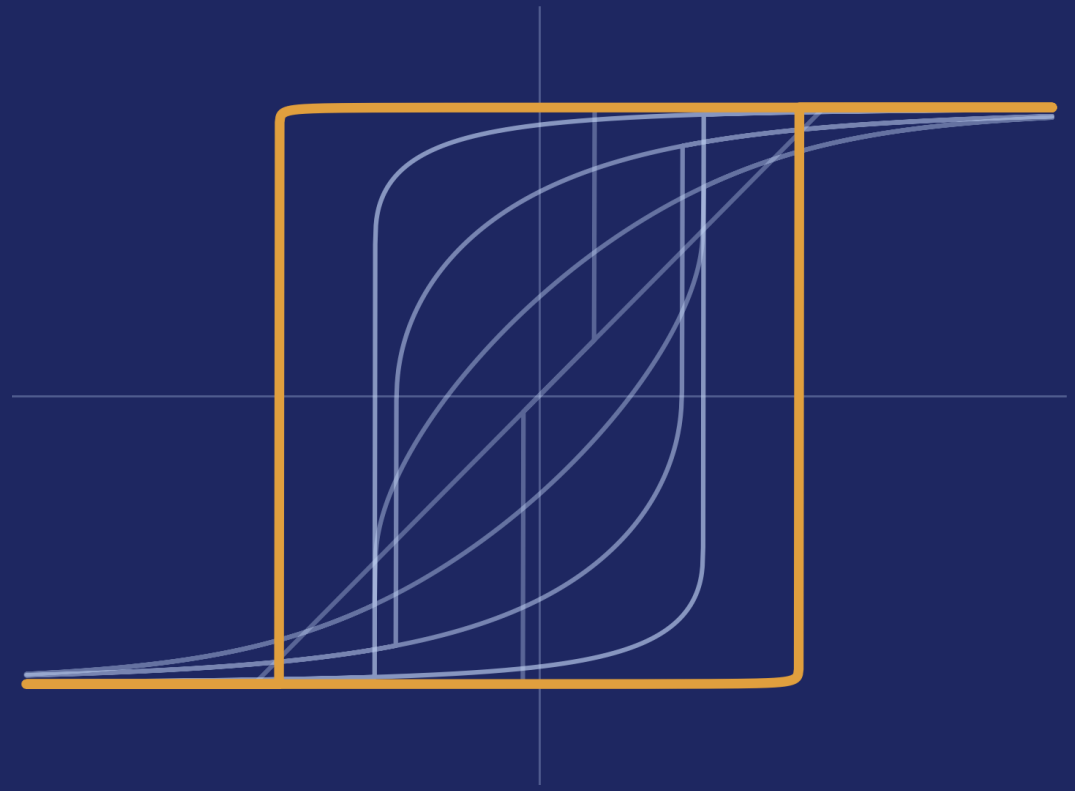
European School on Magnetism 2026

Magnetization Reversal Processes



From the hysteresis loop to current-induced switching

Oscar Grånäs

20 August 2026

Based on J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009) — Chapter 1 (Introduction) and Chapter 7 (Micromagnetism, domains and hysteresis).

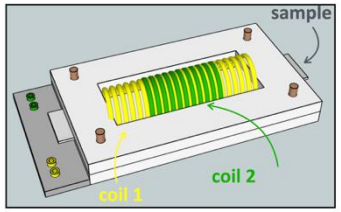
The Hysteresis loop

Tracing B(H)

Function generator

low-frequency drive

Yoke + sample



N_1 primary turns

Secondary coil N_2

senses $d\Phi/dt$

Op-amp integrator

y-channel: B from the integrated emf

Shunt resistor R_1

$U_1 = R_1 I_1$

x-channel: H from Ampère's law

OUTLINE

Structure of the lecture

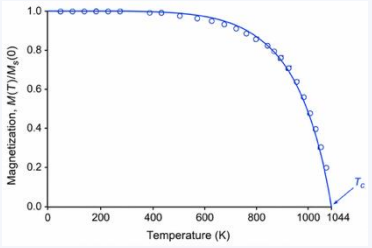
Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials (Cambridge, 2010); the current-driven and all-optical sections follow the primary literature cited on each slide.

PIERRE WEISS, 1907

The molecular field

1 Thermal disorder overcomes ordering

The magnetization collapses to zero at a sharp Curie point: 628 K for Ni, 1044 K for Fe, 1388 K for Co. A continuous phase transition. Figure shows $M(T)/M_s(0)$ vs temperature for Fe.



2 Estimates of "internal molecular field"

$$H_W = n_W M \qquad n_W = \frac{3k_B T_C}{\mu_0 n m^2}$$

Every moment feels an internal field proportional to the magnetization itself; mean-field theory then fixes the coupling from the measured Curie point.

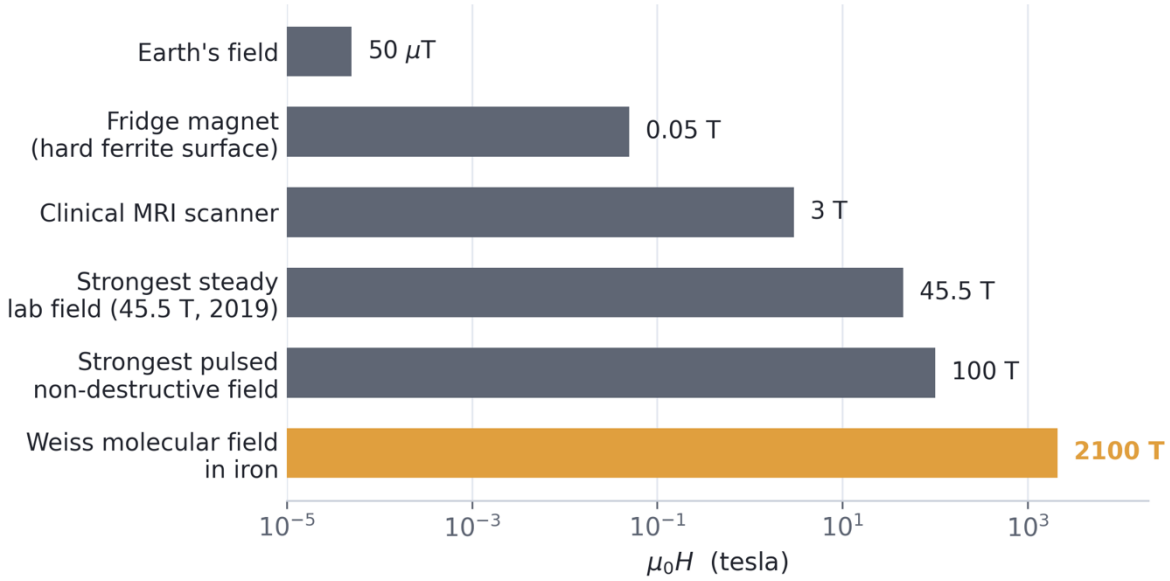
3 Reading n_W off the measured curve

$\chi = C/(T - T_C)$ → $T_C = n_W C$ → $n_W = T_C/C$

Above T_C plot $1/\chi$ against T: the slope gives $1/C$ and the intercept on the temperature axis gives T_C. Two numbers from one straight line fix the coupling.

The example of iron

$n_W \approx 10^3$ — an internal field of about 2000 tesla, three orders of magnitude larger than the magnetization it is supposed to explain.



How big is 2000 tesla? Field magnitudes on a logarithmic scale.

The paradox

Maxwell's $\nabla \cdot B = 0$ insists such a field be continuous across the surface — yet nothing remotely this large is ever measured outside a bar of iron. Heisenberg (1929): the molecular field is not a magnetic field at all. It is electrostatic exchange, a consequence of the Pauli principle:

$$\mathcal{H} = -2\mathcal{J}\mathbf{S}_i \cdot \mathbf{S}_j \quad \text{with } \mathcal{J}/k_B \approx 1\text{–}100 \text{ K}$$

Inspired by J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

1600 → 1935

The hysteresis loop of a ferromagnet

1600 — **Gilbert, De Magnete**

The Earth itself is a great magnet. First “modern” scientific text — the lodestone loses its soul.

1881 — **Ewing names the effect “Hysteresis”**

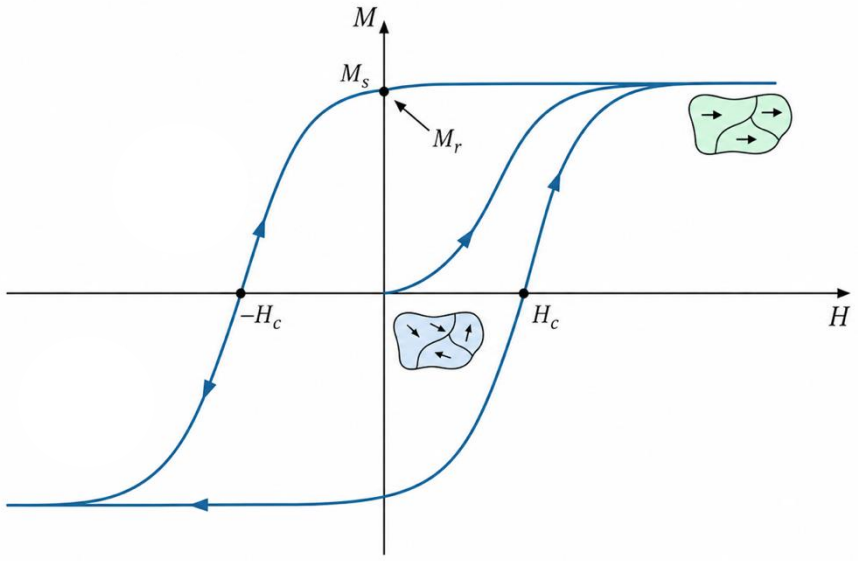
From Greek ὑστέρησις, ‘to lag behind’. M depends not on H alone, but on the history of H.

1919 — **Barkhausen hears noise**

Nickel wires in a pick-up coil, amplifier, loudspeaker: reversal is discontinuous, not smooth.

1935 — **Landau & Lifshitz**

Domain theory put on a firm footing. Ewing’s domains become a calculable object.



A sketch of the hysteresis loop of a ferromagnet, with the domain structure sketched at the virgin state and at saturation.

THE ANSWER IS A

The Stoner–Wohlfarth model, 1948

The four assumptions

1 Coherent rotation

M stays uniform through the particle, |M| = Ms; only its direction changes.

2 Uniaxial anisotropy

A single easy axis, energy Ku sin²θ — magnetocrystalline or from shape.

3 Zero temperature

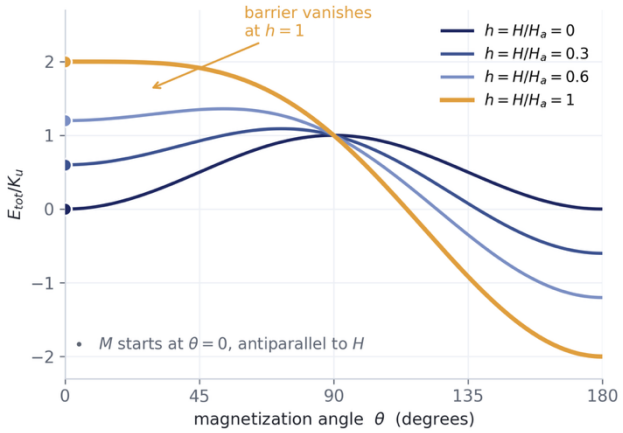
No thermal hopping over barriers; the state is whichever minimum it is in.

4 No interactions

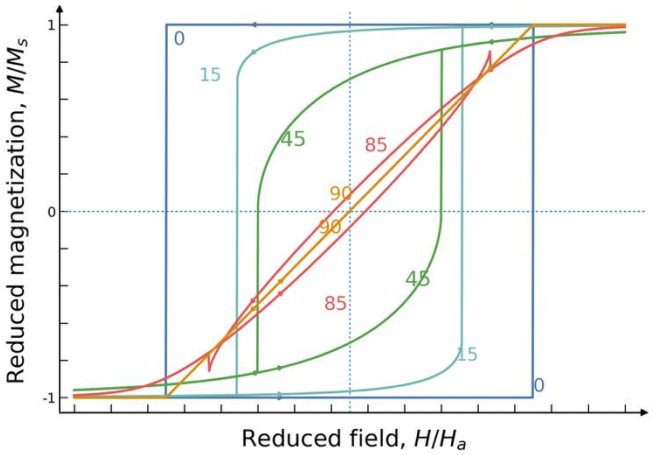
Particles feel the applied field only, not each other.

$$E_{tot} = K_u \sin^2\theta - \mu_0 M_s H \cos(\alpha - \theta) \qquad (7.21)$$

Coey Eq. (7.21) — anisotropy and the Zeeman term



Two minima ⇒ hysteresis. Minimizing over θ gives one or two minima; switching is the irreversible jump when $d^2E/d\theta^2 = 0$.



Hysteresis loops based on the Stoner-Wohlfart model for α = 0–90°. Along the easy axis the loop is square with Hc = Ha = 2Ku/μ0Ms; perpendicular to it there is no hysteresis at all.

E. P. Wohlfarth, 1924–1988. *E. C. Stoner and E. P. Wohlfarth, "A mechanism of magnetic hysteresis in heterogeneous alloys", Phil. Trans. R. Soc. Lond. A 240, 599 (1948).*

DOMAIN OBSERVATION, 1919–1950s

Experimental evidence for domains and wall motion

1919

Barkhausen noise

A bundle of nickel wires inside a pick-up coil, an amplifier and a loudspeaker. Sweeping the field produces audible clicks. The flux changes in discrete jumps, so something of finite size is flipping at a time.

1931

Bitter patterns

A colloid of fine magnetic particles collects at the stray field above a domain wall. Under an optical microscope the domain pattern of a polished surface appears ,domains are objects, not bookkeeping.

1949

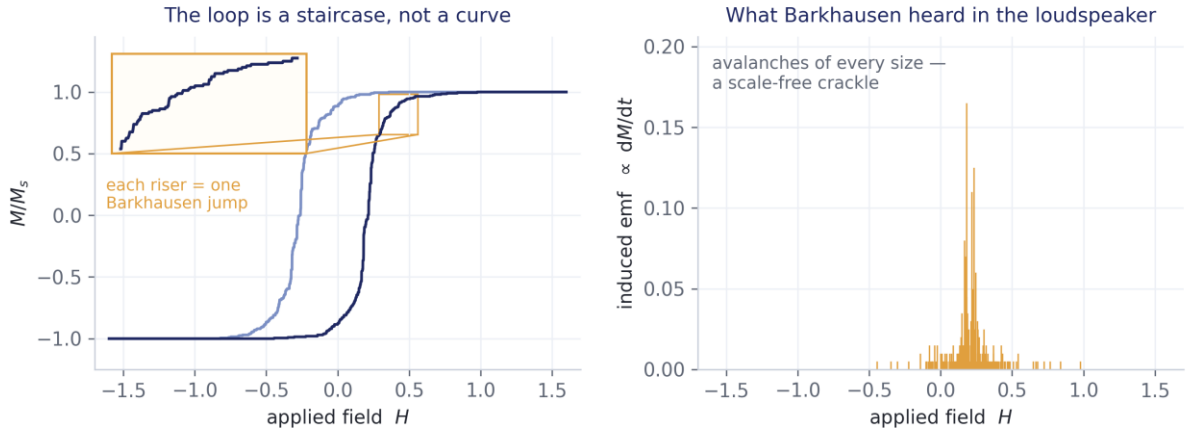
Williams, Bozorth & Shockley

Bitter patterns on a picture-frame single crystal of Si–Fe. The walls are watched moving under an applied field, and the measured flux change matches the wall displacement. The mechanism is settled.

1950s–

Kerr and Lorentz microscopy

Thin films open a new zoo: Néel walls, Néel lines, cross-tie walls, maze domains, vortex states. Reversal in a film element is a different problem from reversal in a bulk crystal.



A Preisach model of 400 interacting pinning sites. The magnetization advances in avalanches of every size, each inducing a voltage pulse in a pick-up coil — the crackle Barkhausen heard in 1919, now a non-destructive probe of microstructure.

MICROMAGNETICS

The micromagnetic energy functional

$$\varepsilon_{tot} = \varepsilon_{ex} + \varepsilon_a + \varepsilon_d + \varepsilon_Z + \varepsilon_\sigma + \varepsilon_{ms}$$

Coey (7.4)

Atomic structure is averaged away. M(r) varies in direction only — its magnitude is fixed at Ms — and the equilibrium configuration is whatever minimizes the volume integral of these six densities, subject to the boundary conditions.

Exchange $\varepsilon_{ex} = A(\nabla \mathbf{e}M)^2$ Resists twist of the magnetization. A ≈ 10 pJ m^{-1} (permalloy 10, Co 31); A ≈ $JS^2Z_c/2a_o$. wish is approximately $k_bT_c/2a_0$, or $A(T)=M_S(T)D_{SW}/2g\mu_b$

Magnetocrystalline anisotropy $\varepsilon_a = K_1\sin^2\theta$ Determines easy axes. K_1 = 0.1 to 10^4 kJ m^{-3} which is the widest range of any term in the energy functional, and decisive for the hysteresis.

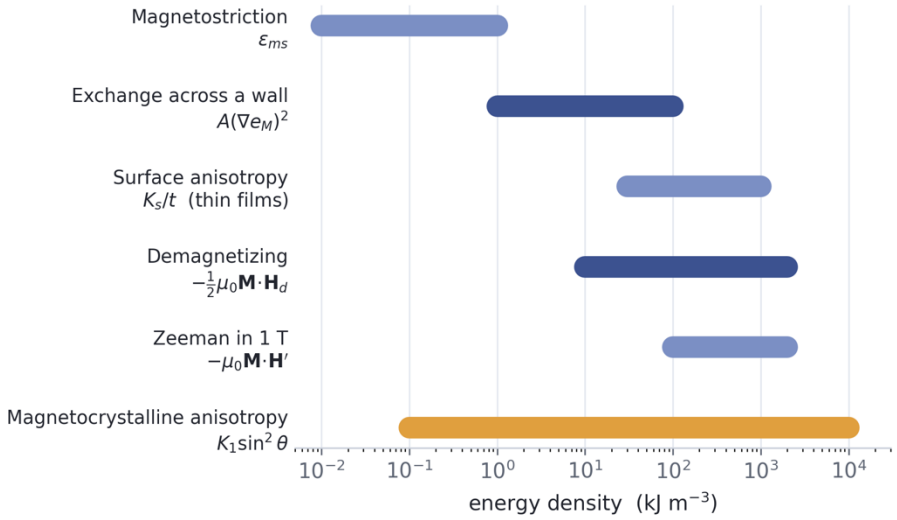
Demagnetizing (self-energy) $\varepsilon_d = -\frac{1}{2}\mu_o M \cdot Hd$ The price of magnetic charge $M \cdot e_n$ at surfaces and $\nabla \cdot M$ in the bulk. Up to 2000 kJ m^{-3}. Driving domain formation.

Zeeman $\varepsilon_Z = -\mu_o M \cdot H'$ The only term containing the applied field. It defines the magnetization process and the shape of the loop.

Applied stress $\varepsilon_\sigma = -\Sigma\sigma_{ij}\,\varepsilon_{ij}$ Equivalent to a uniaxial anisotropy $K_u = (3/2)\lambda s\sigma$. Usually small but explains why magnets may be sensitive to handling.

Magnetostriction $\varepsilon_{ms} = \frac{1}{2}\int(e-\varepsilon)\cdot c\cdot(e-\varepsilon)$ Frustrated magnetostrictive strain. Low, < 1 kJ m^{-3} — but it is what inhibits closure domains.

Domains exist because ε_d is expensive. Walls are thin because ε_{ex} and ε_a both are.



Typical magnitudes. Ranges after Coey §7.1.

Equilibrium

$$e_M \times H_{eff} = 0$$

no torque anywhere

Exchange length

$$l_{ex} = \sqrt{A/\mu_0 M_s^2} \approx 3 \text{ nm}$$

shortest scale M can twist on

Wall types and the magnetic hardness parameter κ

Bloch in bulk, Néel in films

A Bloch wall rotates the magnetization in the plane of the wall and makes no ∇·M, so in bulk it costs nothing magnetostatically and is what forms. A Néel wall rotates within the plane of the domain magnetization: it pays volume charge but no surface charge — the winning trade in a thin film. That crossover is the next slide.

Material	Ms (MA m^{-1})	A (pJ m^{-1})	K_1 (kJ m^{-3})	δw (nm)	γw (mJ m^{-2})	κ
$Ni_{80}Fe_{20}$ permalloy	0.84	10	0.15	2000	0.01	0.01
Fe	1.71	21	48	64	4.1	0.12
Co	1.44	31	410	24	14.3	0.45
$BaFe_{12}O_{19}$ hard ferrite	0.38	6	330	13.6	5.6	1.35
$Nd_2Fe_{14}B$	1.28	8	4900	3.9	25	1.54
$SmCo_5$	0.86	12	17200	2.6	57.5	4.30

Data originates with Coey, Table 7.1 (selected rows). $\kappa = \sqrt{(K_1/\mu_0 M_s^2)}$ is the magnetic hardness parameter.

Not every wall is 180°

Cubic crystals with ⟨100⟩ easy axes form 90° closure walls of energy $\sqrt{(AK_1c)}$; with ⟨111⟩ easy axes, 71°, 109° and 180° walls cost 0.5, 1.5 and 2.2 times $\sqrt{(AK_1c)}$.

The importance of κ

κ < 1 — sample shape wins over the crystal, walls are wide and cheap, the material is soft. κ > 1 — anisotropy wins, walls are a few nanometres wide and expensive, and the material holds its magnetization against its own demagnetizing field. Permalloy and $SmCo_5$ differ by 400× in κ and six orders of magnitude in coercivity.

A wall with energy per unit area behaves like a membrane — so it can be pinned. Coercivity in real materials is a competition between pinning a wall and nucleating a reverse domain.

Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

Bloch wall width and wall energy density

1 **Two surviving terms**

In a 180° Bloch wall the magnetization rotates in the plane of the wall, so $\nabla \cdot M = 0$ everywhere: no magnetic charge, no demagnetizing field. Exchange versus anisotropy.

$$\varepsilon_{tot} = \int \left[A\left(\frac{\partial\theta}{\partial x}\right)^2 + K\sin^2\theta \right] dx$$

2 **The Euler equation gives equipartition**

Minimizing the integral yields $A(\partial\theta/\partial x)^2 = K\sin^2\theta$. The two energy densities are equal at every point in the wall.

$$A(\partial\theta/\partial x)^2 = K\sin^2\theta$$

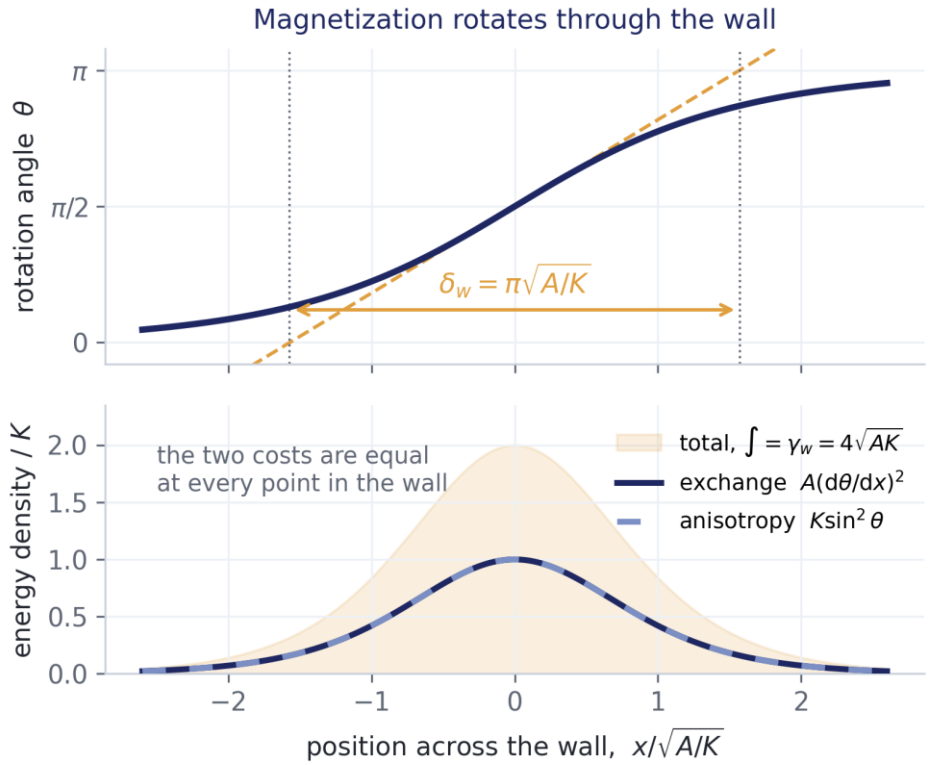
3 **The wall profile**

Integrating once gives the wall equation, with $\theta = \pi/2$ at the centre. The magnetization only approaches 0 and π asymptotically, so the width has to be defined by a convention.

$$x = \sqrt{A/K}\,\ln\tan(\theta/2)$$

$$\delta_w = \pi\sqrt{A/K} \qquad \gamma_w = 4\sqrt{AK}$$

Coey (7.17), (7.18).
Typically 10–100 nm and ~1 mJ m^{-2}.



Why a wall? Flipping the magnetization from one atomic plane to the next would cost about $2A/a \approx 0.1$ J m^{-2}, a hundred times more than a wall. Width increases with increased exchange and decreases with increased anisotropy. The wall is an effect of this balance , since energy is attached to its area, the wall behaves like an elastic membrane, which is exactly why it can be pinned, bowed and depinned.

THIN FILMS

Néel walls in thin films: the t < δ crossover

Why the Bloch wall is less relevant in thin films

In a Bloch wall the magnetization turns out of the film plane. In bulk that is free — ∇·M = 0, no charge anywhere. In a film it is ruinous: the out-of-plane component lands charge on the top and bottom surfaces, and the thinner the film the more it costs.

Néel's estimate: an elliptical cylinder

Model the wall as a cylinder of elliptical cross-section t × δ. The Néel wall points its magnetization across the wall, the Bloch wall along the film normal, so the two see different demagnetizing factors:

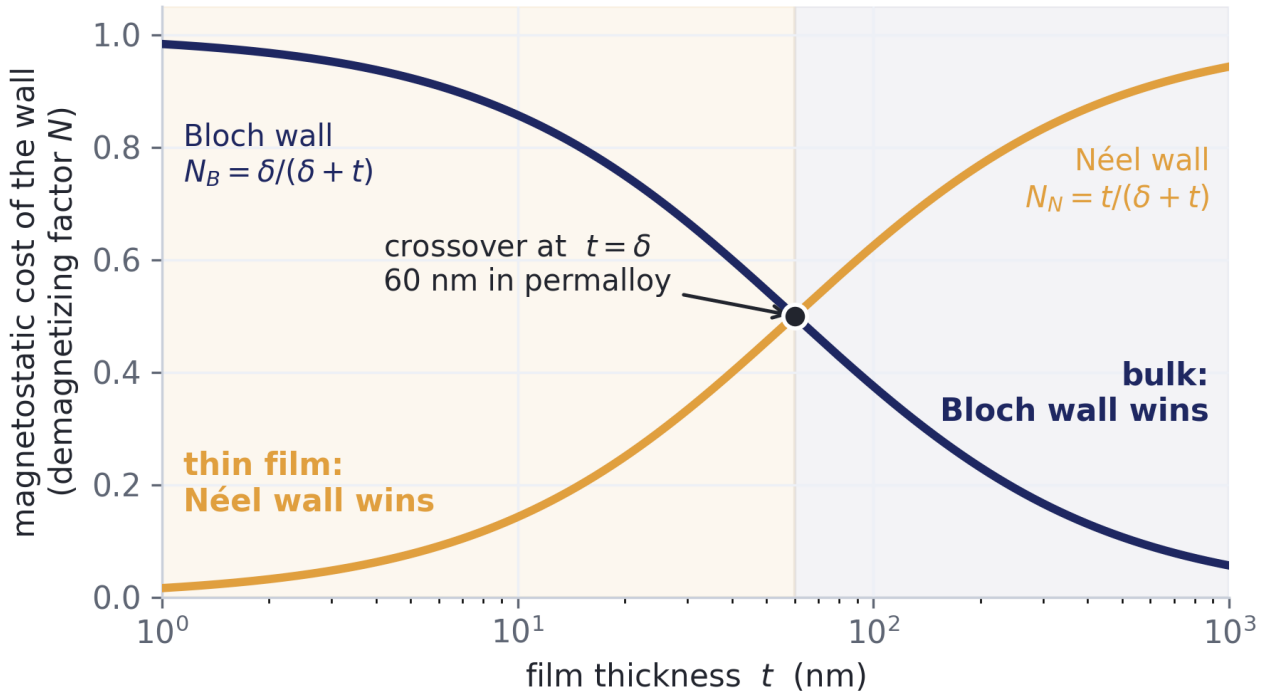
$$N_B = \frac{\delta}{\delta + t} \qquad N_N = \frac{t}{\delta + t}$$

The Néel wall wins for t < δ.

The fauna it brings with it

Néel lines are strips of Néel wall inside a Bloch wall where the rotation sense reverses — stable defects that only full saturation removes. **Bloch lines** are the converse — a strip of Bloch wall where two Néel segments of opposite chirality meet. A **cross-tie wall** alternates the rotation sense along its length; thicker films add vortex cores, with Néel caps at the surfaces and Bloch character in the middle.

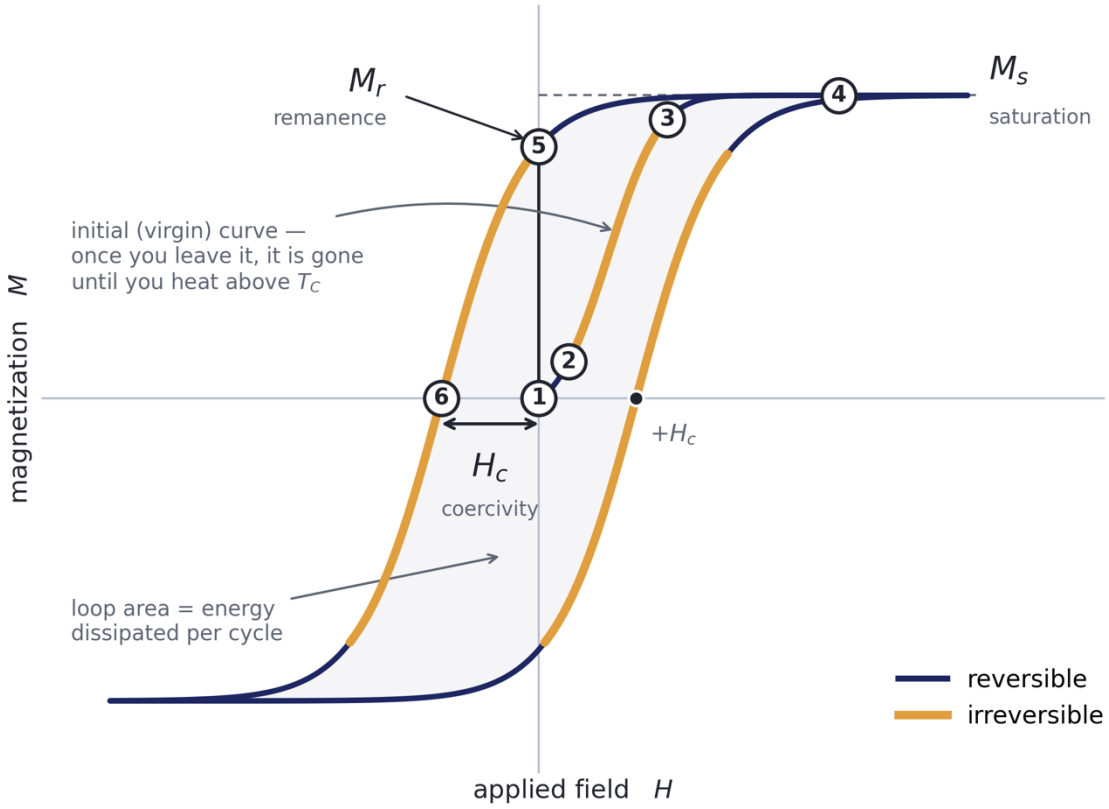
a cross-tie wall



Néel's thin-film argument, plotted. In bulk (t ≫ δ) the Bloch wall has demagnetizing factor 0 and the Néel wall 1, so Bloch wins; as the film thins the two swap. The measured crossover in permalloy is 60 nm, and the Bloch wall itself narrows in a film to cut its stray field — so the real picture is messier.

Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

Stages of the magnetization curve



1 → 2 reversible — **Reversible wall bowing**

Walls stay pinned but bulge like a soap film under pressure $2\mu_0 MsH$. This is where the initial susceptibility χi and the Rayleigh laws $M = \chi iH + vH^2$ live. Remove the field and the walls snap back.

2 → 3 irreversible — **Barkhausen jumps**

Walls tear free of pinning centres and sweep the sample, wiping out all but the most favourably oriented domain. This is where the loop area — the dissipated energy — is generated.

3 → 4 reversible — **Coherent rotation**

One domain left. M rotates against the anisotropy towards H, saturating at the anisotropy field $Ha = 2Ku/\mu_0 Ms$. Approach to saturation: $M = Ms(1 - a/H - b/H^2) + \chi_0 H$.

at 4 intrinsic — **Saturation — Ms is revealed**

The domain structure has been eliminated. What is left is the spontaneous magnetization inside a single domain: exchange and the atomic moments, falling to zero at TC.

4 → 5 reversible — **Rotation back to the easy axis**

Reduce H to zero and M rotates back onto the nearest easy direction — reversible. But the domains do not spontaneously come back. What survives is the remanence Mr.

5 → 6 irreversible — **Nucleation, then wall motion**

Reverse domains nucleate at defects and surface asperities, and their walls propagate. The reverse field that brings M back to zero is the coercivity Hc.

M_s: saturation magnetization — INTRINSIC

Set by exchange and the atomic moments alone — 1720, 1370 and 485 kA m^{-1} for Fe, Co and Ni — and falling to zero at TC. No amount of metallurgy changes it; the record has not moved in a century.

M_r: remanence — EXTRINSIC

What survives when the field returns to zero. Set by the domain structure and by texture: Ms/2 for a random array of Stoner–Wohlfarth particles, approaching Ms if you align them during pressing.

H_c: coercivity — EXTRINSIC

Anisotropy sets the ceiling, $Hc < 2Ku/\mu_0 Ms$. Defects — pinning centres and nucleation sites — set the value you actually measure, typically 20–30 % of it. That gap is Brown's paradox.

Loop stations 1–6 after Coey, Fig. 7.21. Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

Domain-wall mobility and pinning

A field is a pressure on the wall

$$p = 2\mu_0 M_s H$$

Move the wall by δx and the Zeeman energy changes by $2\mu_0 M_s H \delta x$ per unit area. The wall has a surface tension γw, so it responds like an elastic membrane: it bows first, and only then breaks free.

How fast does it move?

$$v_w = \mu_0 \eta_w (H - H_p)$$

Mobilities ηw run from 1 to 1000 m s^{-1} mT^{-1}; about 100 is typical of a permalloy film, so 0.1 mT already drives walls at 10 m s^{-1}. The linear law collapses above roughly 100 m s^{-1}. In electrical steel eddy currents set the limit: **$\eta w = \rho / 2G\mu_0^2 Mst$ with $G = 0.1356$** gives 2.1 m s^{-1} mT^{-1} for a 350 µm sheet — and ηw ∝ 1/t, so films are far faster.

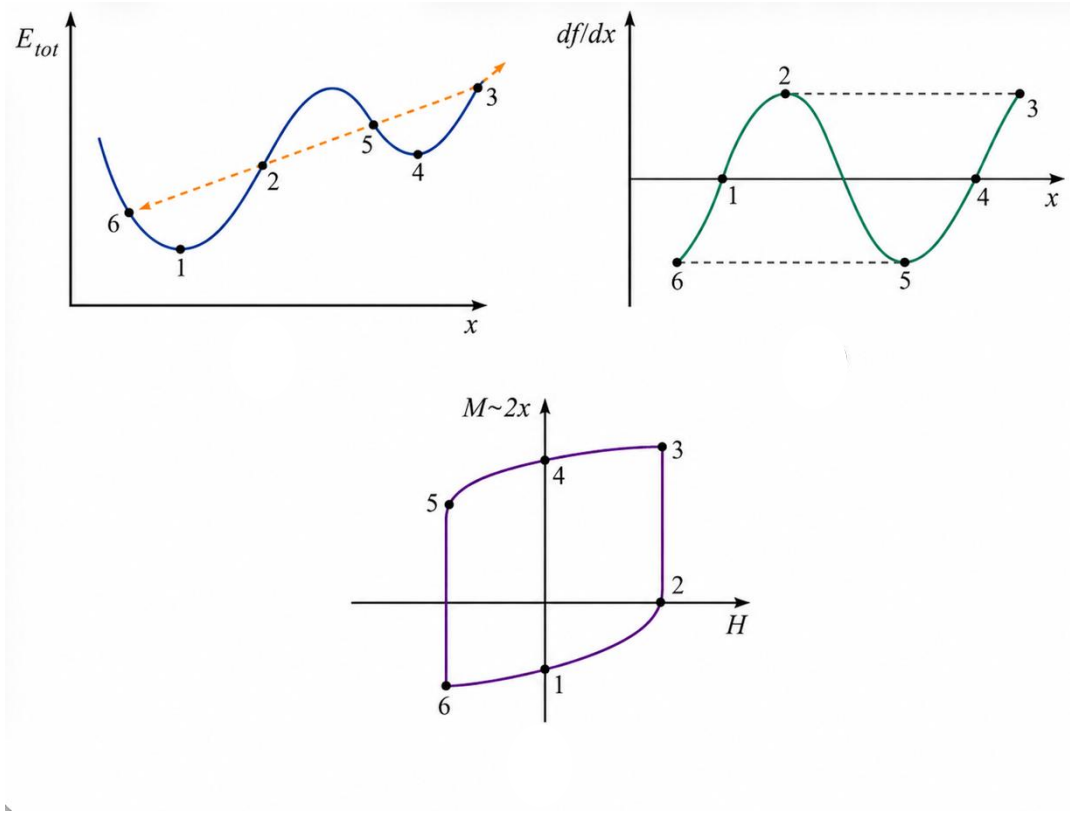
Strong pinning and weak pinning

Because γw is an energy per unit area, anything that changes A or K traps the wall. Planar defects are the strongest centres — the whole wall changes energy at once — and pinning peaks when the defect is about δw across; contrast is greatest at a void, K = A = 0. Weak pinning is the statistical alternative: many point defects, and fluctuations in how many the wall contains.

Rayleigh laws, 1887

$$M = \chi_i H + \nu H^2$$

The low-field limit: a reversible linear term plus an irreversible quadratic one, leaving a remanence $\nu H^2/2$. Coey (7.37)–(7.39).



$$E_{tot} = f(x) - 2\mu_0 M_s H x$$

Adapted from Coey, Fig. 7.20. With increasing field the wall jumps there and the magnetization changes discontinuously. Cycle the field and the jumps trace a hysteresis loop: every ingredient of a real loop is in this one picture.

Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

Brown's paradox and nucleation-limited coercivity

Brown's theorem, 1947

$$H_c \geq \frac{2K_1}{\mu_0 M_s} - \mathcal{N} M_s$$

For a homogeneous, uniformly magnetized ellipsoid the coercivity cannot be less than the anisotropy field minus the demagnetizing field. Rigorous — no approximations, no model of the reversal at all.

The paradox

Real magnets never get close. It is a long struggle, after each new hard material is introduced, to reach even 20–30 % of the anisotropy field. A rigorous theorem and a laboratory both being right, and disagreeing by a factor of four.

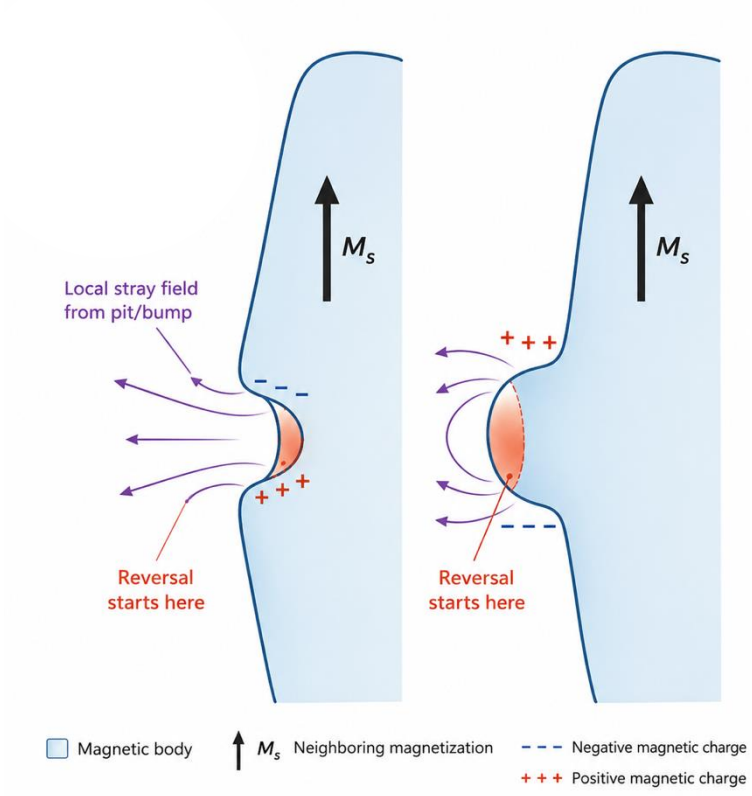
The resolution: incorrect assumptions

Real materials are inhomogeneous and have a surface. Reversal does not begin everywhere at once but in a nucleation volume of order δw^3 at a weak point. A pit or bump concentrates the demagnetizing field, so the local reverse field exceeds the applied one and that region flips long before the bulk would.

The empirical fix

$$H_c = \alpha_K \frac{2K_1}{\mu_0 M_s} - N_{eff} M_s$$

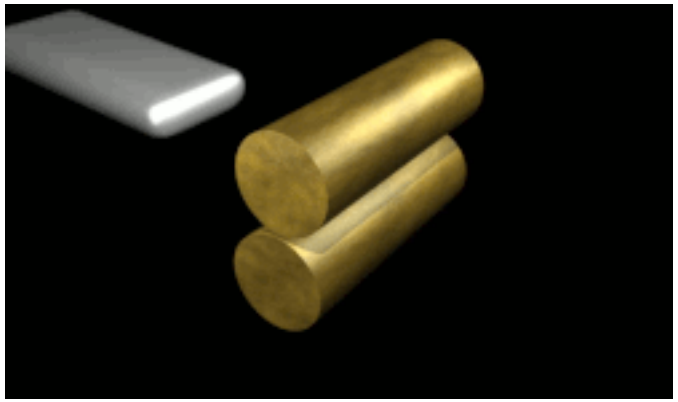
Kronmüller: fit αK and Neff to experiment, and admit what you don't know.



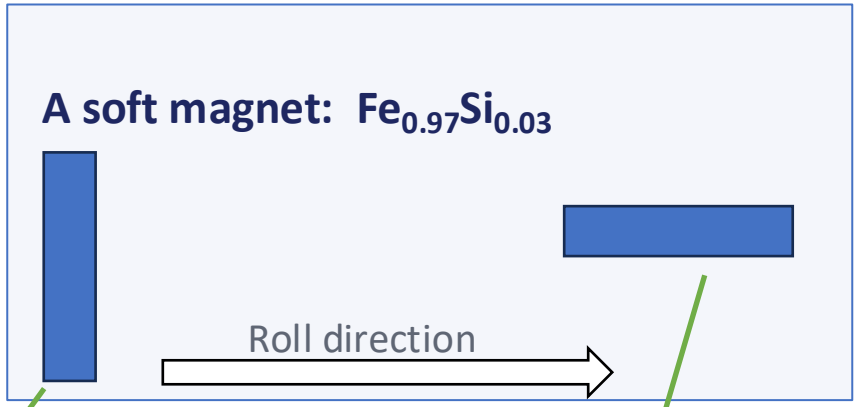
A pit or a bump makes its own stray field. In the second quadrant that field adds to the applied one, so the shaded region reverses first.

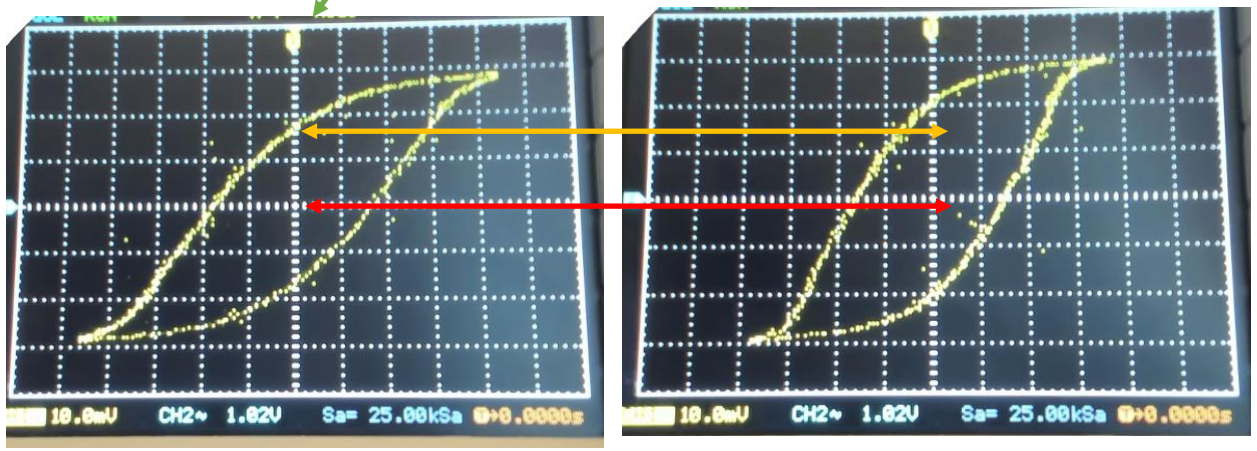
Following J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

In practice – sample orientation influences hysteresis

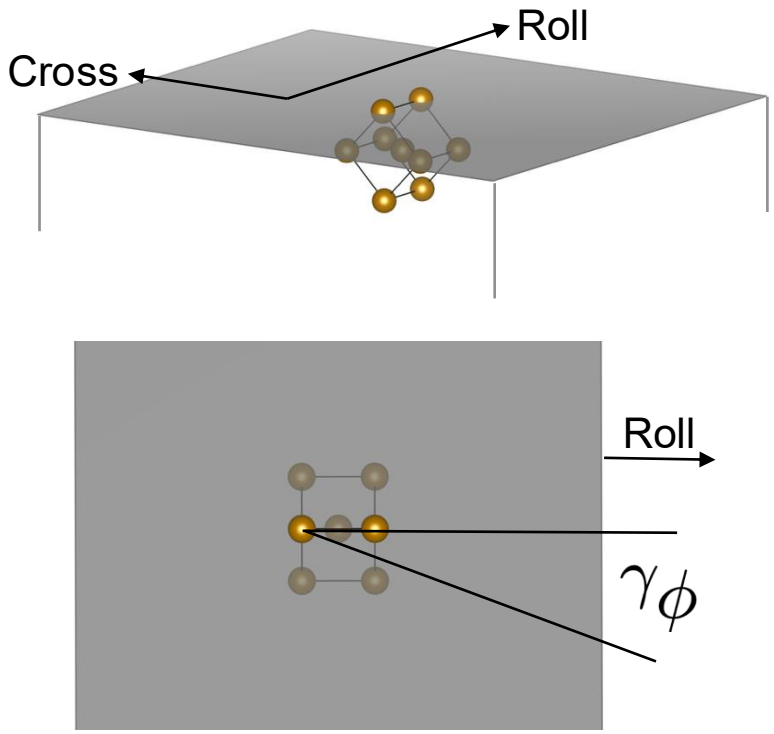


Wikipedia

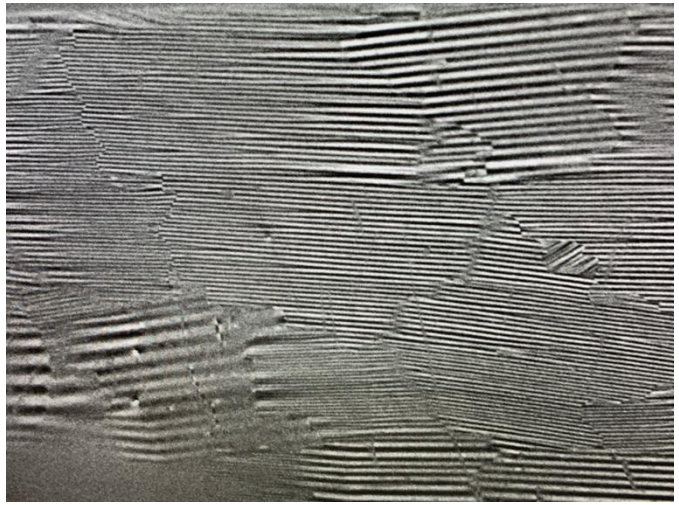




Why the loop depends on the direction measured



Rolling textures the sheet. Grains share an orientation with a [001] easy axis near the rolling direction, so the anisotropy survives averaging over grains.



Stripe domains. Alternately ±[001] along the rolling direction, separated by 180° walls.

Roll direction — walls move

The field lies along the easy axis, so every domain is already aligned or anti-aligned with it.

Magnetizing costs only wall motion: favourable stripes grow, unfavourable ones shrink, and no moment leaves its easy axis.

Steep and square — high permeability, low coercivity, small loop area.

Cross direction — moments rotate

The field is now roughly 90° from the in-plane easy axis, and both stripe types are perpendicular to it.

Moving walls buys nothing: the moments themselves must rotate in the plane, against the anisotropy barrier.

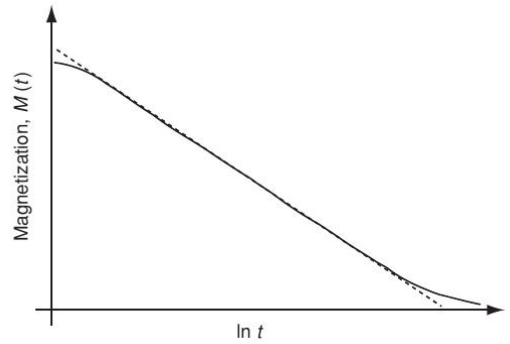
Sheared — lower permeability, more field to saturate, larger loss.

Both directions reach the same saturation — only the route there differs, and the difference is the anisotropy energy paid on the way.

Same sheet, same loop-tracer — only the orientation in the yoke changes. Rotation in iron must overcome $K_1 \approx 48$ kJ m^{-3}, an anisotropy field of order 50 mT, which is what widens and shears the transverse loop.

Domain image and sheet geometry from the laboratory material; anisotropy constant for bcc Fe after J. M. D. Coey, Magnetism and Magnetic Materials, Table 5.2.

Magnetic viscosity and precessional switching



Coey, Fig. 7.23. The magnetic states observed around the hysteresis loop are metastable. The variation is logarithmic — a straight line against ln t.

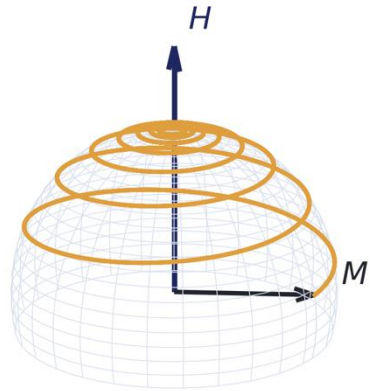
Magnetic viscosity

$$M(t) \approx M(0) - S_v \ln(t/\tau_0)$$

Every state around the loop is metastable, so the loop depends on sweep rate: measure more slowly and the coercivity comes out lower. Sv acts as a fluctuation field and is proportional to temperature. The logarithm follows from a flat distribution of barriers — which is why it fails at very short and very long times.

Two activated processes

The magnetic after-effect is the diffusion of atomic defects — vacancies, carbon, nitrogen — with activation energies of 1–2 eV and attempt frequencies of order 10^{15} s^{-1}; the walls wait for the defects to move. Separately, in a hard magnet, **a reverse domain can nucleate from a thermal fluctuation alone**, reversing a volume of order δw^3 with no defect involved. Hence ageing permanent-magnet arrays before use: anneal 50–100 K above the operating temperature so the easy reversals happen where they do no harm.



precession about *H*, damped, relaxing into alignment

At the other end of the time axis

$$\frac{dM}{dt} = \gamma\mu_0 M \times H - \frac{\alpha}{M_s} M \times \frac{dM}{dt} \qquad \omega_L = \gamma\mu_0(H + H_a) \quad 28\ \mathrm{GHz\,T^{-1}}$$

A moment in a field precesses rather than simply turning: 28 GHz per tesla, and the anisotropy field counts too. The Landau–Lifshitz–Gilbert equation adds the damping without which it would never settle. Drive a film perpendicular to its easy axis and the magnetization precesses out of plane, meets a demagnetizing field of order a tesla, and is whipped round in about 0.01 ns. Coherent reversal is fast; domain-wall motion is slow.

Figures and content after J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge University Press (2009).

CURRENT-INDUCED SWITCHING

Spin-transfer torque

Angular momentum has to go somewhere

A current crossing a magnetized layer comes out spin-polarised along ζ. Send it into a second magnet whose moment m points elsewhere and the spin component transverse to m is absorbed within about a nanometre as the electrons dephase. That angular momentum must go to the lattice magnetization: a torque, with no magnetic field involved.

Two terms, and only two

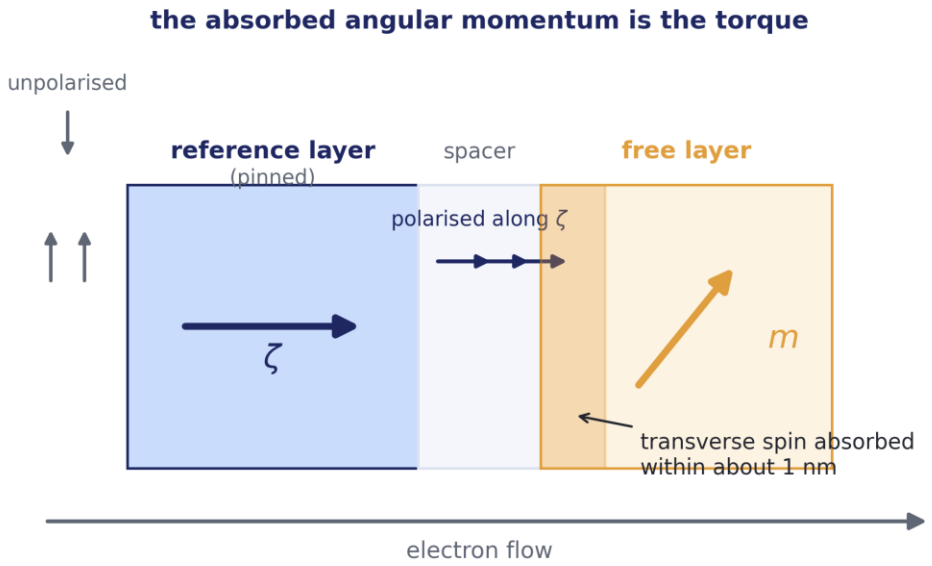
$$\dot{m} = -\gamma\, m \times B_M + \alpha\, m \times \dot{m} + \frac{\gamma}{M_s} T$$

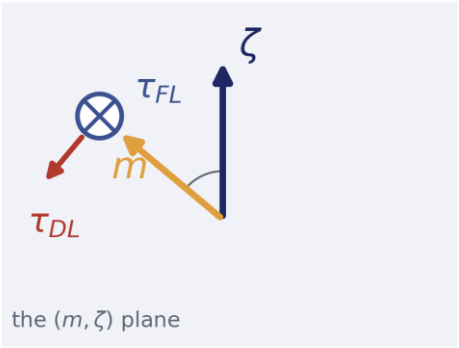
$$T = \tau_{FL}\, m \times \zeta + \tau_{DL}\, m \times (m \times \zeta)$$

Manchon et al. (2019), Eqs. (1)–(2)

The two terms

The field-like term τFL m × ζ acts similar to ordinary field would — it makes M precess, and alone it can never switch anything, because precession conserves energy. **The damping-like term** τDL m × (m × ζ) has the form of Gilbert damping but with a sign you control through the current. Reverse the current and it becomes **anti-damping**: it pumps energy in, the precession cone opens, and the magnet switches. That is the whole trick — a current that cancels the damping of a nanomagnet.





Berger and Slonczewski, independently, in 1996. Both predicted that a current through a magnetic multilayer would exert a torque; both were right, and neither result was believed for several years. Experimental confirmation came from nanopillar spin valves in 1999–2000, and STT is now how every commercial MRAM cell is written.

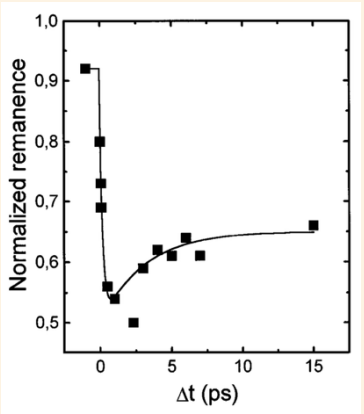
L. Berger, Phys. Rev. B 54, 9353 (1996); J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996); review: Ralph & Stiles (2008).

S. Mangin et al., Current-induced magnetization reversal in nanopillars with perpendicular anisotropy, Nat. Mater. 5, 210 (2006); A. Manchon et al., Rev. Mod. Phys. 91, 035004 (2019).

Optically induced magnetization dynamics

Demagnetization in a picosecond

Beaurepaire (1996): a femtosecond pulse on nickel quenches the magnetization within about a picosecond — far faster than spin–lattice relaxation in the ground state. The light itself cannot supply the angular momentum: the total photon spin in a realistic pulse is orders of magnitude too small.



Open question:
Where does the angular momentum go, and what does the helicity do?

Inverse Faraday effect

Circularly polarized light acts as an effective field along the beam, its sign set by the helicity. Simulations taking B_{eff} = 20 T reproduced the intensity window.

Angular momentum from light

The photon spin is handed straight to the spin system. Discarded early on quantitative grounds — the available photon angular momentum is far too small.

A femtosecond pulse is 10^3–10^4 times shorter than the shortest field or spin-current pulse able to switch a magnet, and under 10 fJ is expected to suffice for a 20 × 20 nm² element.

Transient ferromagnetic-like state

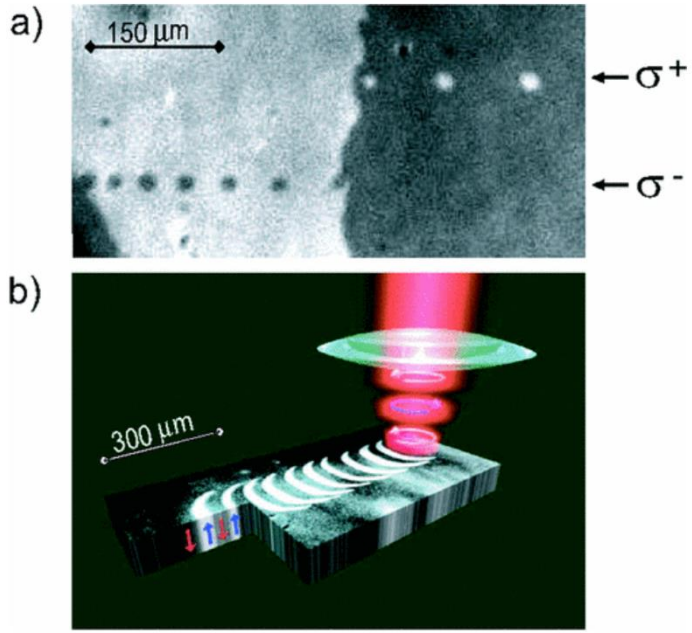
The sublattices demagnetize at different rates and align transiently in parallel, against their exchange. Helicity enters only through the absorption.

E. Beaurepaire et al., Phys. Rev. Lett. 76, 4250 (1996); C. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007); mechanisms as summarized in A. R. Khorsand et al., Phys. Rev. Lett. 108, 127205 (2012).

Reversal with no magnetic field

Stanciu (2007): circularly polarized femtosecond pulses reverse ferrimagnetic GdFeCo with no applied field.

- Reversed in a reproducible manner by a single 40 femtosecond circularly polarized laser pulse, without any applied magnetic field.
- Combined result of femtosecond laser heating of the magnetic system to just below the Curie point and circularly polarized light simultaneously acting as a magnetic field.
- Direction of the opto-magnetic switching is determined only by the helicity of light.

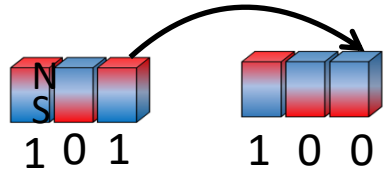


Data transmission, Optical fibers are fast and energy efficient - current record transfer rate of 1840 Gbit/s

UPPMAX, Ångström House 2

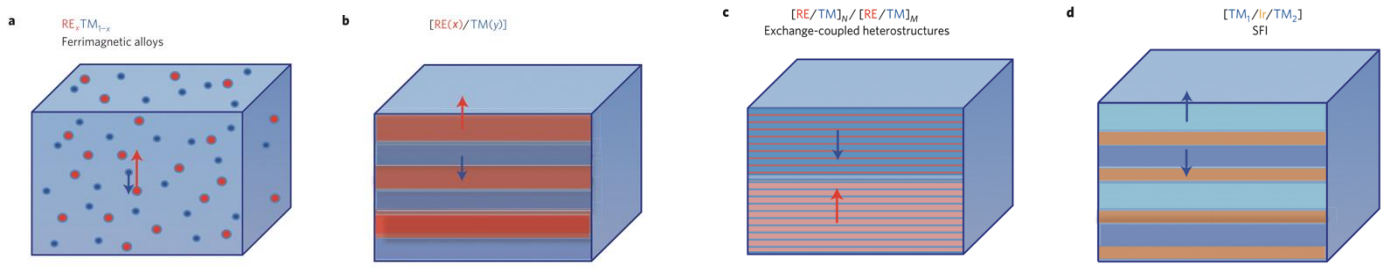
~10^4 mismatch!

Data storage, Magnetic recording - energy efficient, but slow, 0.3Gbit/s



. D. Stanciu et al., Phys. Rev. Lett. 99, 047601 (2007); mechanisms as summarized in A. R. Khorsand et al., Phys. Rev. Lett. 108, 127205 (2012).

Sublattice compensation decides if switching occurs



RE–TM alloys **GdFeCo, TbCo, DyCo, HoFeCo** AO-HDS for every rare earth tried, but only in a narrow window near 25 at.% RE — exactly the range where the sublattices compensate.

RE/TM multilayers **[Tb/Co], [Ho/CoFe]** The first AO-HDS seen in multilayers. An alloy and 0.3 nm and 2.5 nm bilayers of the same average composition all switch.

Coupled heterostructures **$[Tb/Co]_n$ on $[Tb/Co]_{25-n}$** Switching follows the compensation temperature of the whole stack: AO-HDS for N = 25–15, thermal demagnetization below.

RE-free synthetic ferrimagnet **Co/Ir/CoNiPtCo/Ir** Built to mimic a ferrimagnet with no rare earth. With T_{momp} = 380 K it switches; the version without compensation does not.

Compensation is the criterion

Below the compensation point the net moment follows the rare earth, above it the transition metal. Only materials compensating near or above room temperature switch.

It need not be atomic

Compensation averaged over a 6 nm period works as well as compensation within an alloy — the limit being the thickness that still holds perpendicular anisotropy.

What turns out not to matter

Curie temperatures from near room temperature to above 500 K all switch, and the strong spin–orbit coupling of a heavy rare earth is not required.

S. Mangin, M. Gottwald, C-H. Lambert et al., Engineered materials for all-optical helicity-dependent magnetic switching, Nature Materials 13, 286 (2014).

The exchange spring

The problem it solves

A bit must survive thermal fluctuations for ten years, which wants KuV large, and be written by a head supplying about a tesla, which wants the switching field small. In a single-phase magnet those are the same number: raise Ku and both rise — the recording trilemma of slide 19.

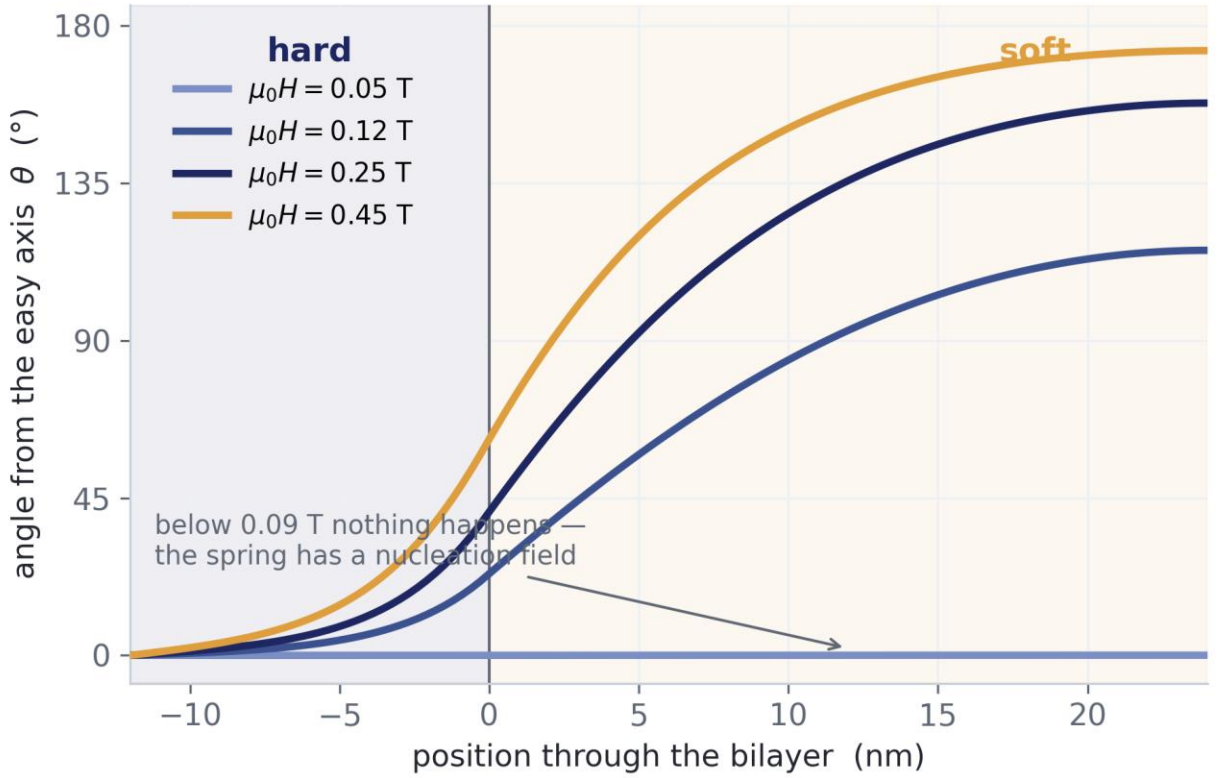
Soft magnet assisted switching via exchange

Put a soft layer on top of the hard one and couple them by exchange. The soft layer has almost no anisotropy, so it rotates in a small field — but not freely, because exchange ties its base to the hard layer. What forms is a partial domain wall compressed into the soft layer: a torsion spring. Wind it up and it pulls on the hard layer from the inside, at an angle — far more efficient than pushing head-on with a field.

Two regimes

$$\mu_0 H_n = \frac{\pi^2 A}{2 M_s t_s^2} \qquad \mu_0 H_{sw} = \frac{2 K_h t_h}{M_s (t_h + t_s)}$$

A thin soft layer is stiffened by exchange and the pair reverses rigidly, at a switching field simply diluted by the extra magnetization. A thick one nucleates a spring instead, at a field falling as $1/t_s^2$. The crossover sits at a few exchange lengths — the same $4l_{ex} \approx 10$ nm that governed the two-hemisphere model on slide 14.



1D micromagnetics of a 12 nm hard layer (Ku = 1.2 MJ m^{-3}) under 24 nm of soft material, A = 10 pJ m^{-1}, Ms = 1 MA m^{-1}, field reversed. Below about 0.09 T nothing happens; above it the spring winds up from the free surface inwards, as the analytic nucleation field predicts.

Exchange-spring principle: E. F. Kneller and R. Hawig, IEEE Trans. Magn. 27, 3588 (1991).

SUMMARY

Four routes to reversal

None of them lowers the energy barrier — they differ in how they get around it.

I

Field

Tilts the landscape until the barrier vanishes.

Wall motion when the field lies along an easy axis — cheap, no anisotropy paid. Otherwise coherent rotation, then curling and buckling once the element outgrows the exchange length.

Brown's paradox: real coercivity reaches only 20–30 % of $2K_1/\mu_0 M_s$.

II

Current

Cancels the damping, so the magnet climbs out by itself.

Spin-transfer torque from a polarizing layer, or spin–orbit torque from a heavy-metal underlayer. The damping-like term changes sign with the current and becomes anti-damping.

7.5×10^7 A cm^{-2} switches a 50 × 100 nm^2 Co/Ni pillar.

III

Light

Removes the barrier thermally; absorption breaks the symmetry.

A femtosecond pulse heats towards T_C. Helicity enters only through magnetic circular dichroism. Needs compensated sublattices near room temperature — or a ferromagnetic film under about 3 nm.

2.6 mJ cm^{-2} absorbed; window $\Delta \approx 1.5$ %, equal to the MCD.

IV

Exchange spring

Changes the path over the barrier, not its height.

A soft layer rotates first and, tied by exchange, pulls on the hard layer from the inside at an angle — far more efficient than pushing head-on with a field.

Write field halved at constant thermal stability.

The thread. One tilts the barrier, one cancels the damping that holds the system behind it, one removes it with heat, and one goes around it. Coercivity was never a material constant — it is a statement about which route the magnetization is allowed to take.

Sources as cited on the individual slides