UNIVERSITY OF CAMBRIDGE

Magnetism in materials

Lecture 6

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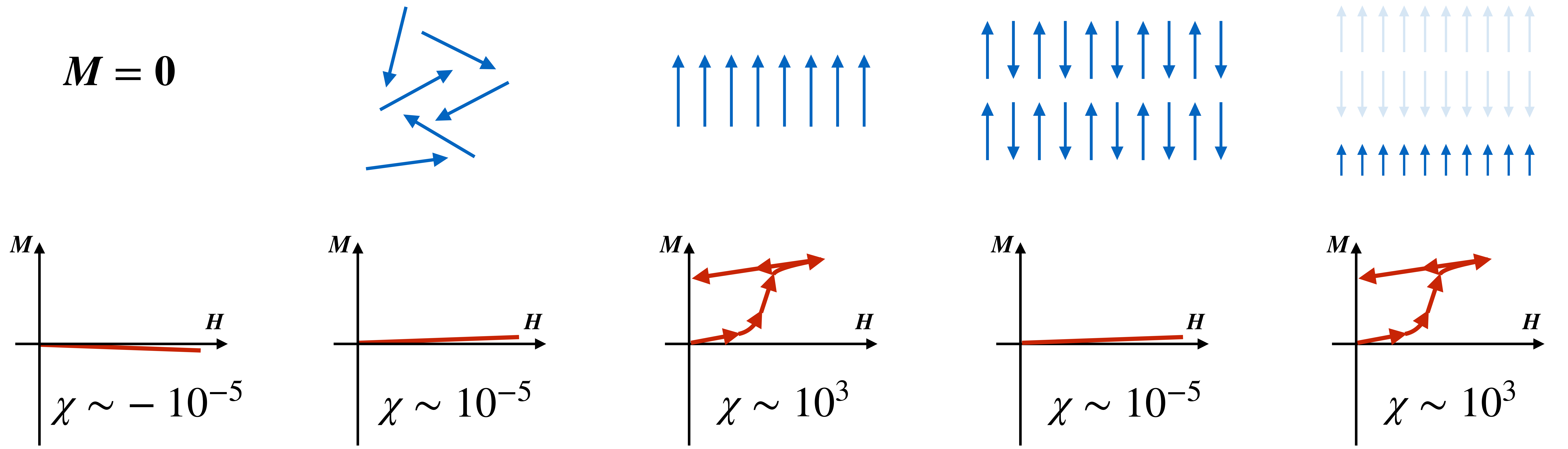
Course B: Materials for Devices

Professor M does Science

http://www.tcm.phy.cam.ac.uk/~bm418/

Classification of magnetic materials

diamagnetic	paramagnetic	ferromagnetic	antiferromagnetic	ferrimagnetic

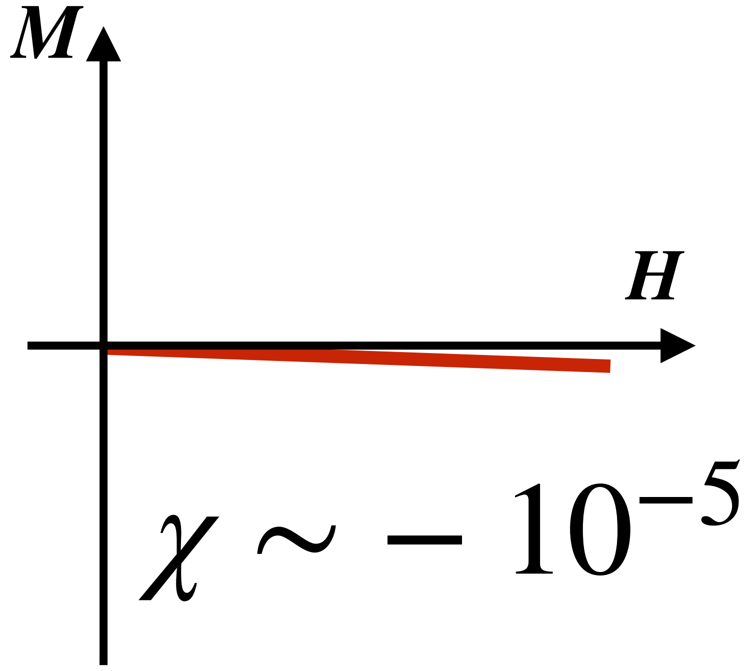


diamagnetic	paramagnetic	ferromagnetic	antiferromagnetic	ferrimagnetic
copper, water	aluminium, magnesium	iron, cobalt, nickel	FeMn, NiO	Fe_3O_4, $NiFe_2O_4$, $Y_3Fe_5O_{12}$

Classification of magnetic materials

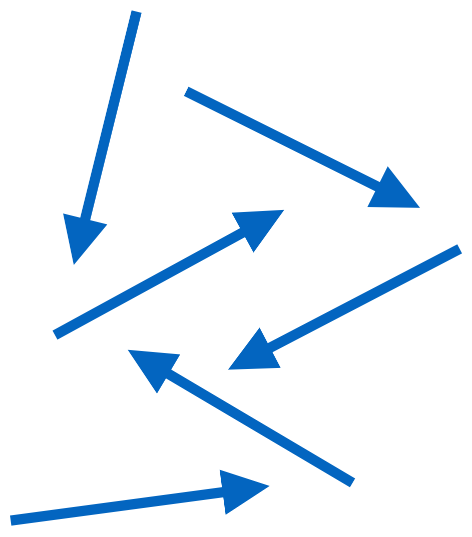
diamagnetic

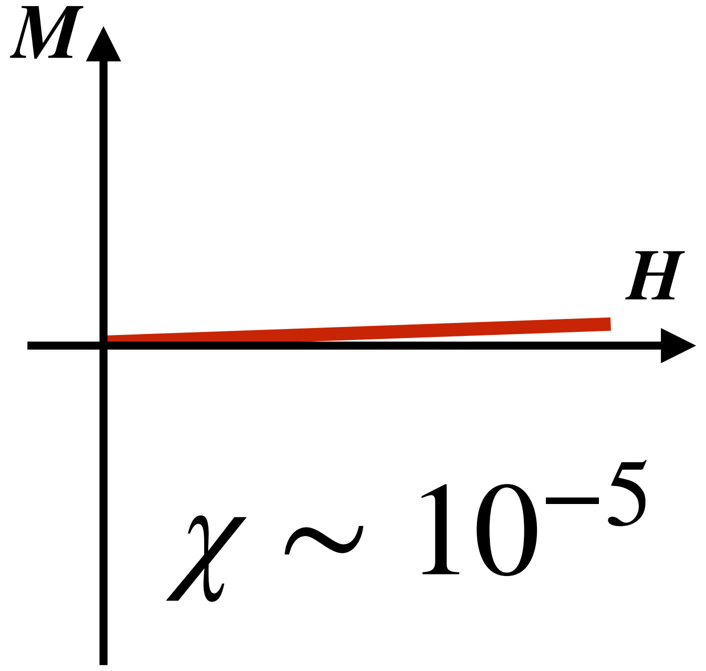
$M = 0$



copper, water

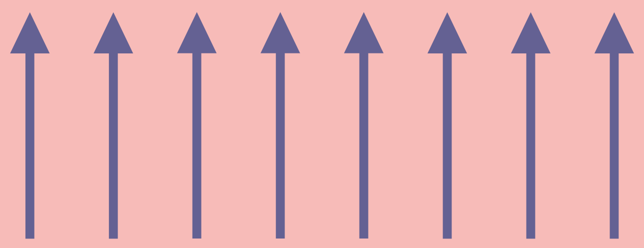
paramagnetic

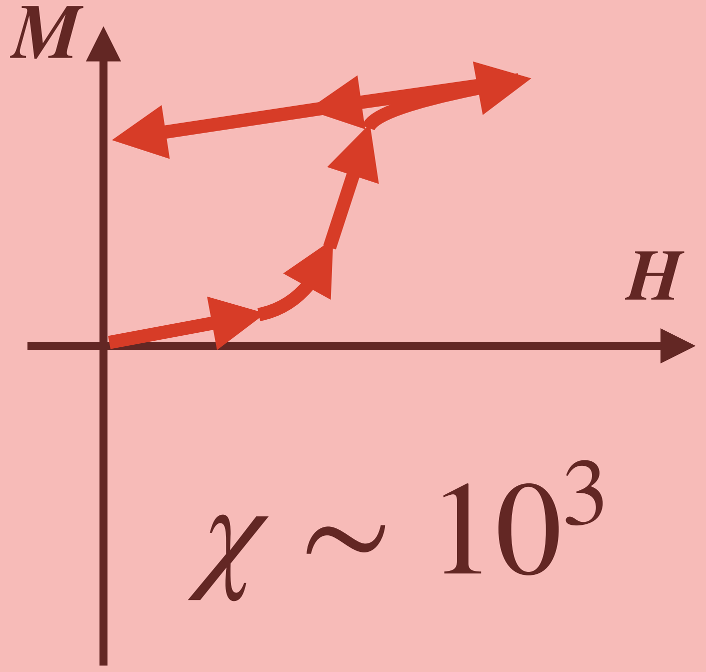




aluminium, magnesium

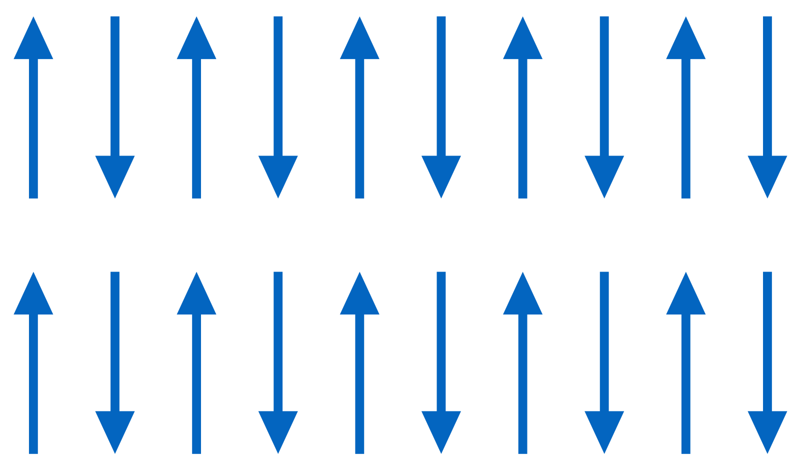
ferromagnetic

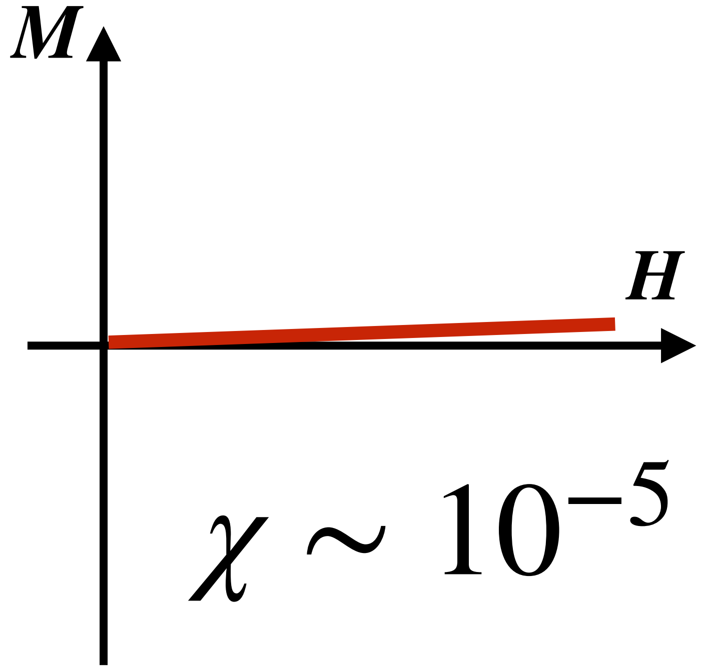




iron, cobalt, nickel

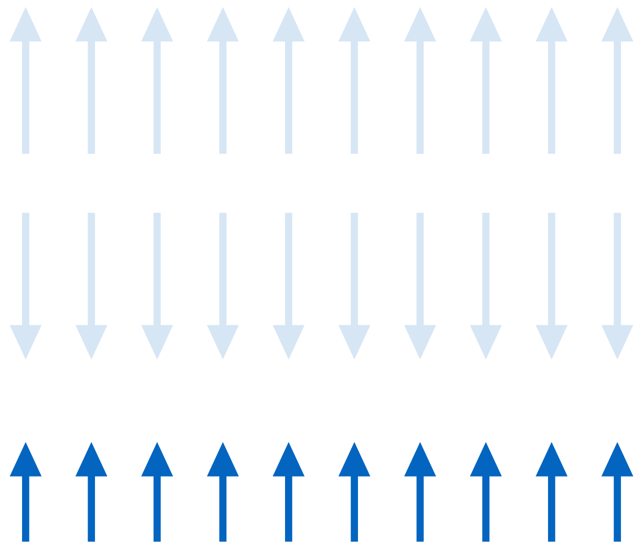
antiferromagnetic

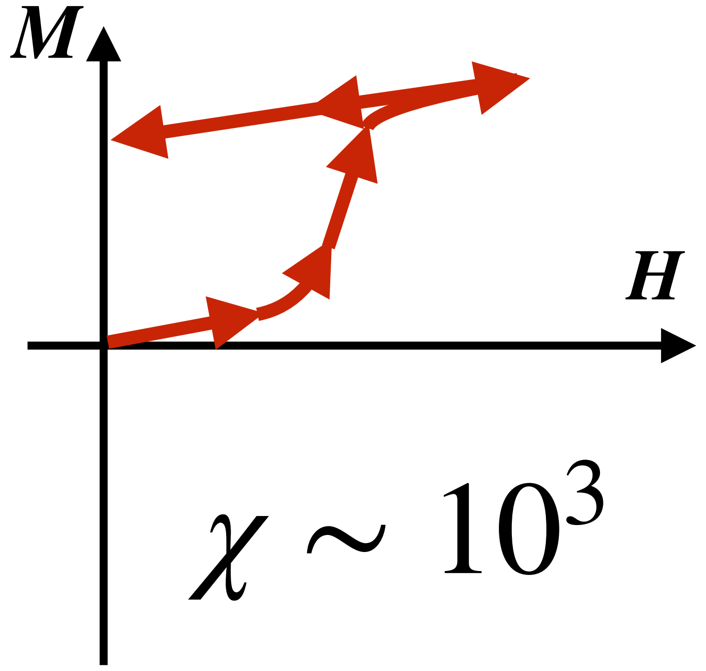




FeMn, NiO

ferrimagnetic





Fe_3O_4, $NiFe_2O_4$, $Y_3Fe_5O_{12}$

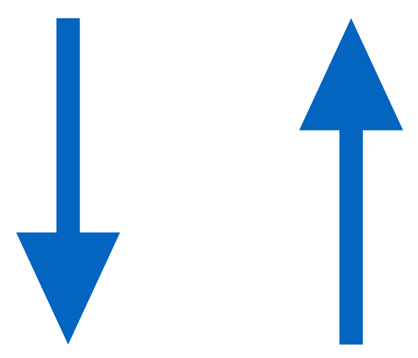
Exchange interaction

- Pauli exclusion principle: no two electrons can occupy the same quantum state

wave function = (spatial part) × (spin part)

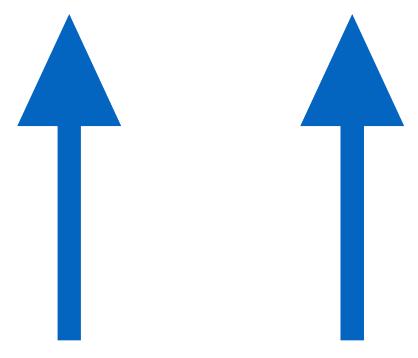
same spatial part

×



different spatial part

×



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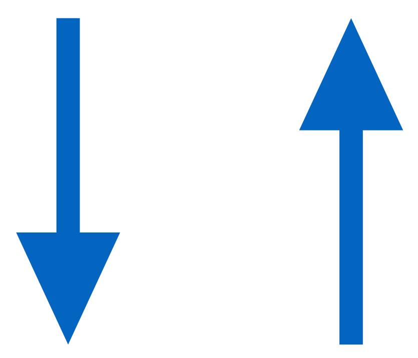
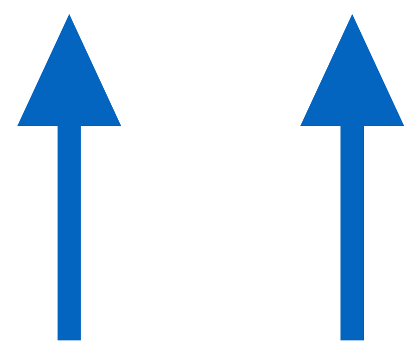


strong Coulomb repulsion

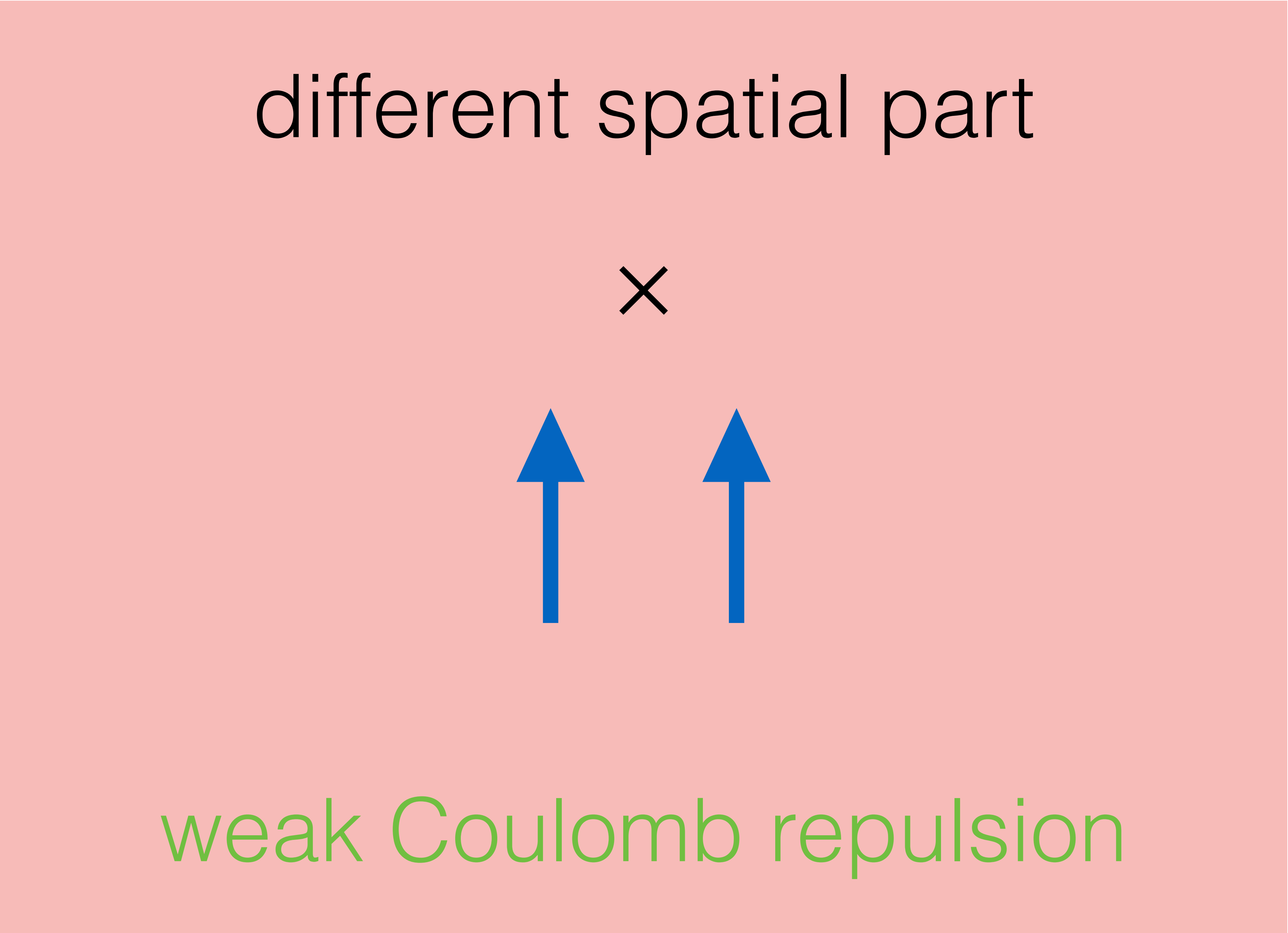
different spatial part

×

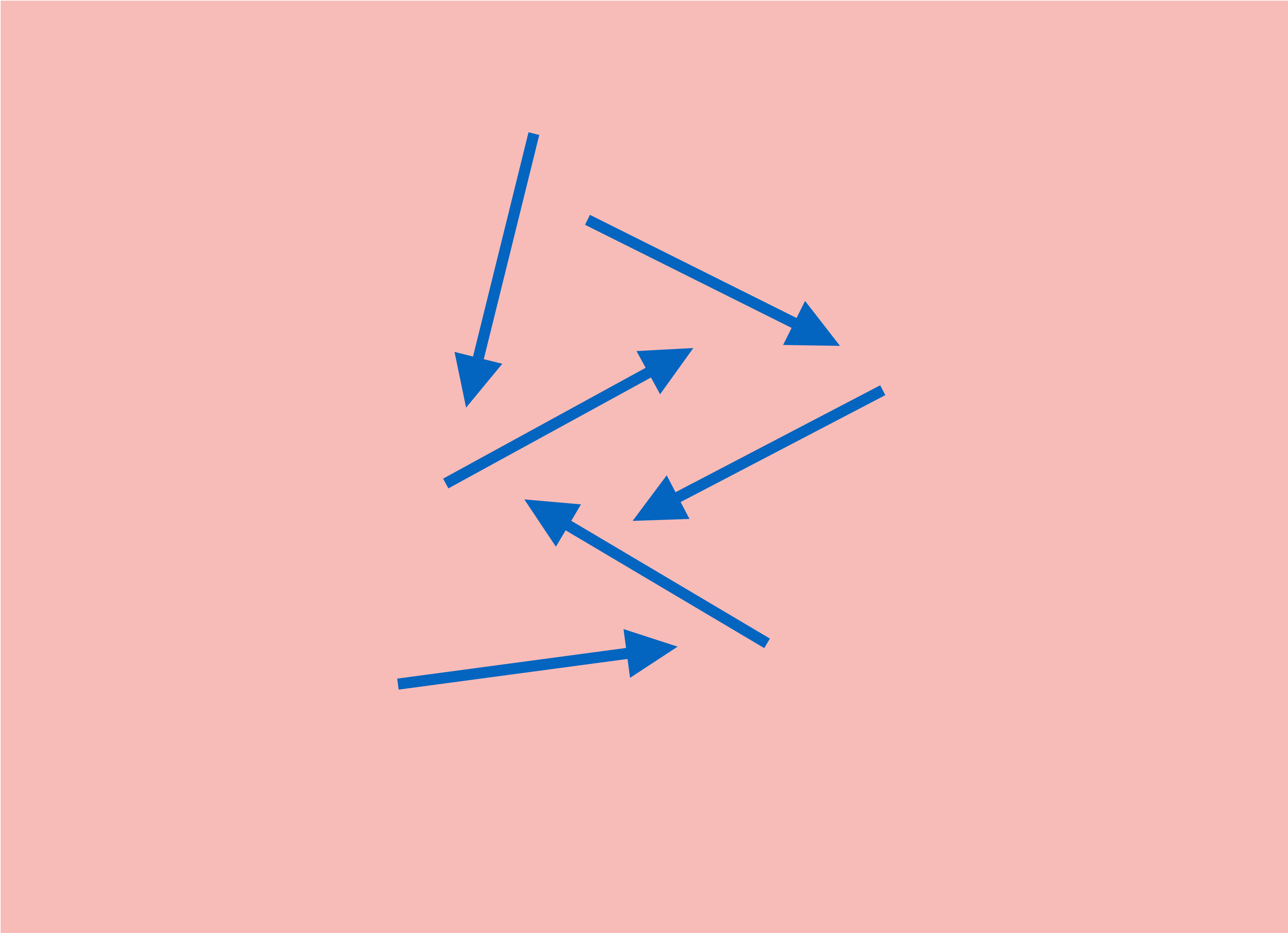


weak Coulomb repulsion

Energy balance

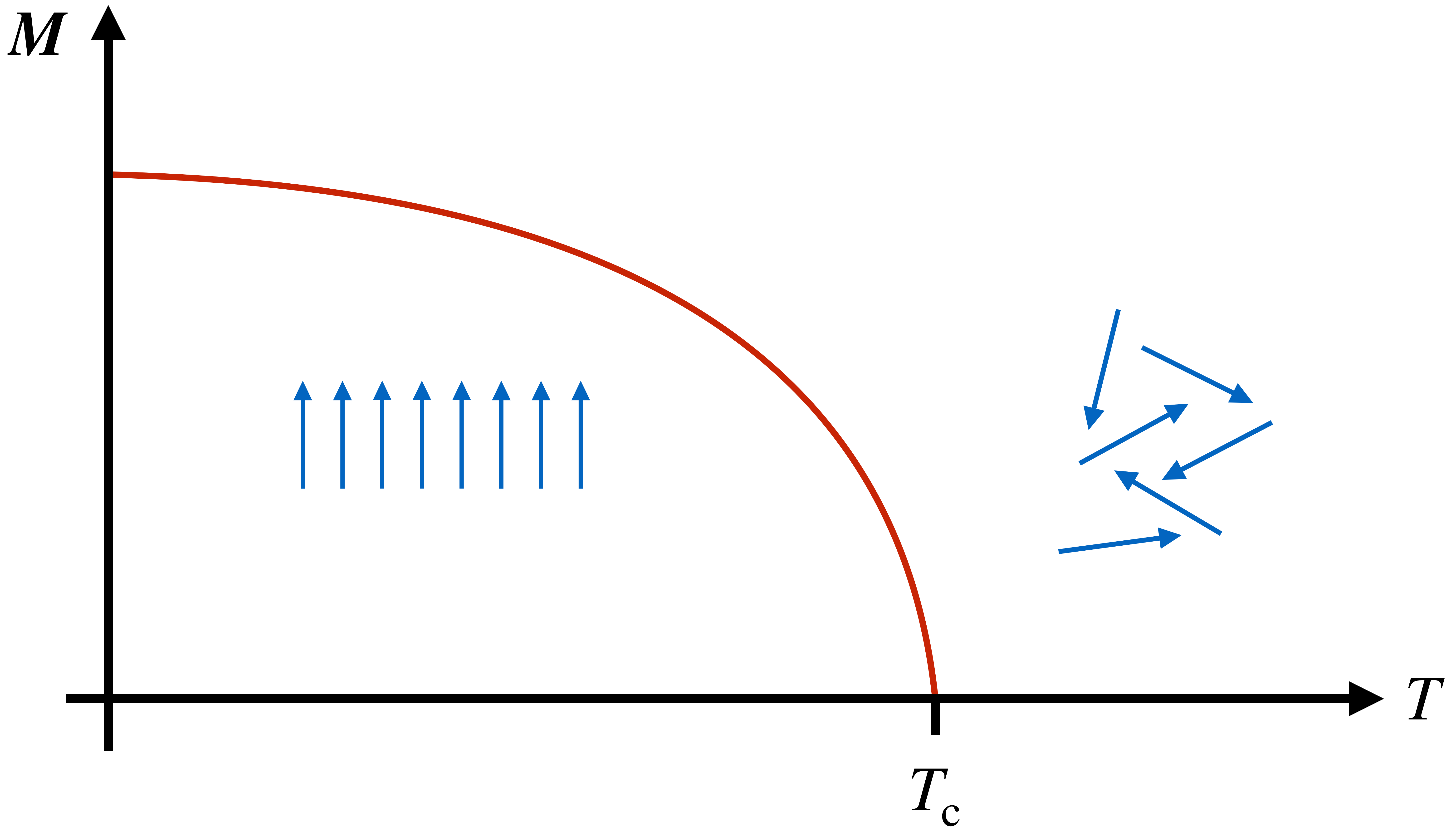


vs.



exchange interaction vs. thermal energy

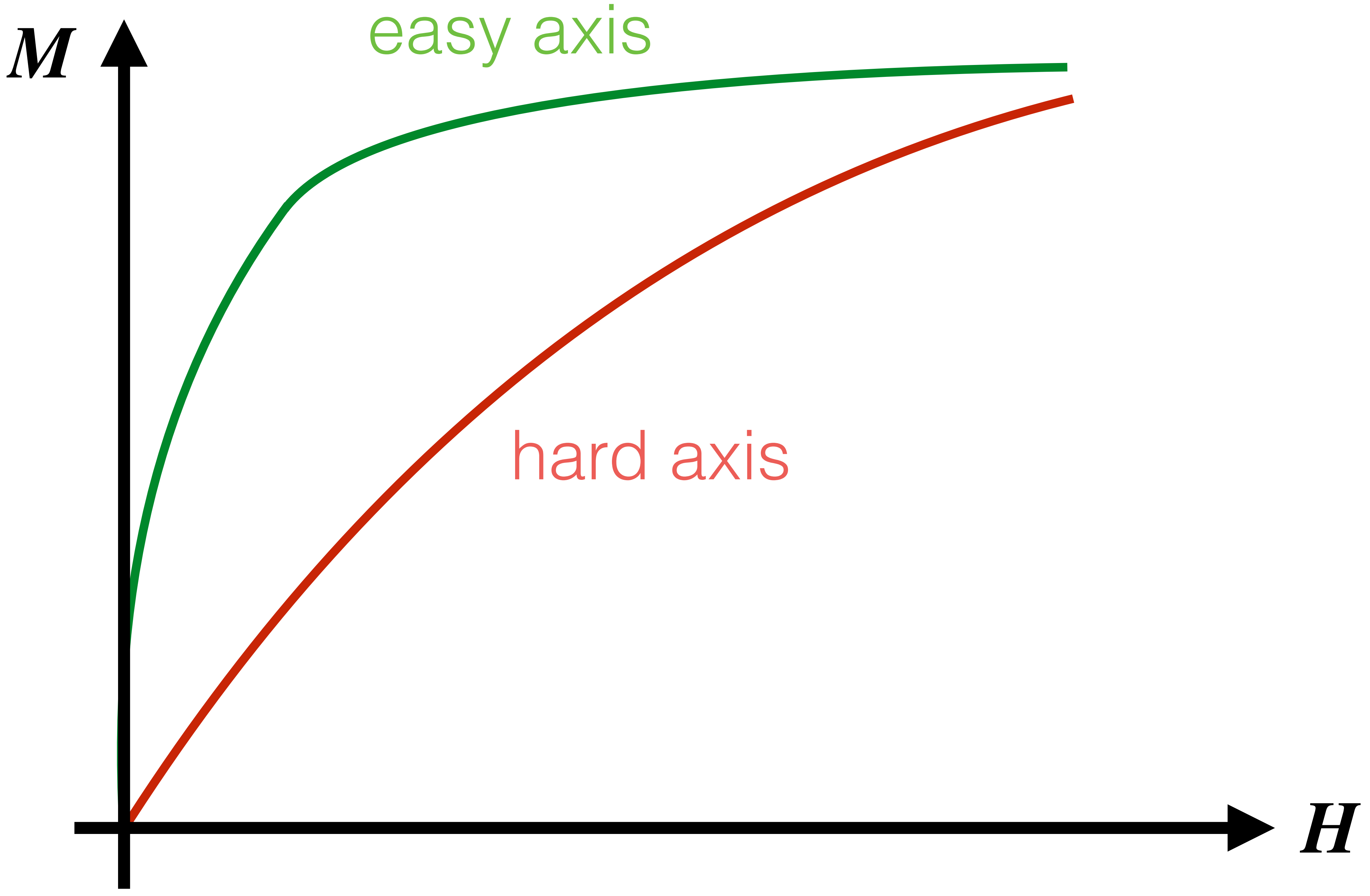
Temperature dependence of ferromagnetic materials



Anisotropy

- Anisotropy: dependence of material properties on direction

Anisotropy: magnetocrystalline anisotropy



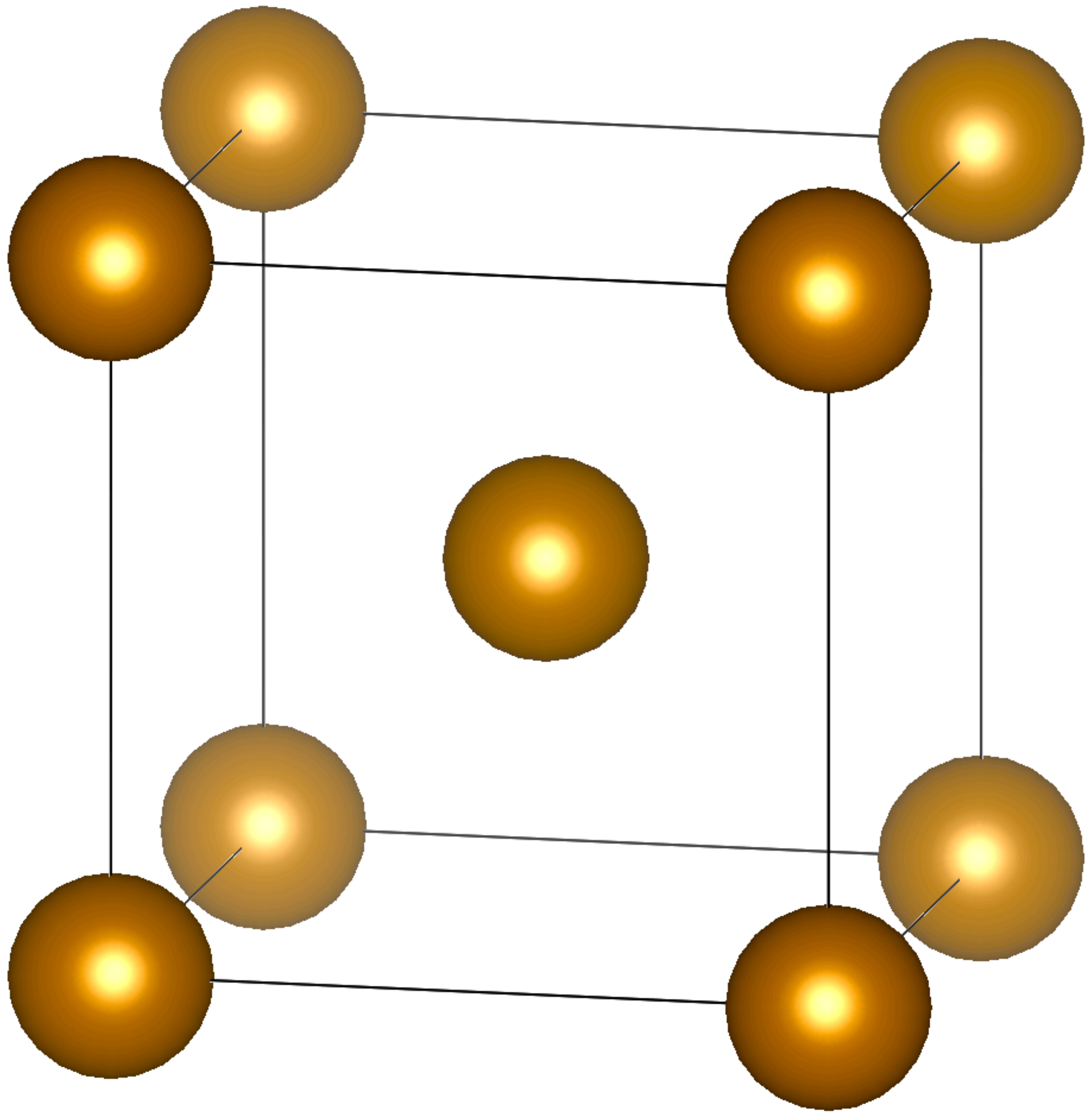
easy axis:

- easy to magnetise sample if field is applied along this direction
- magnetisation saturation reached at relatively low fields

hard axis:

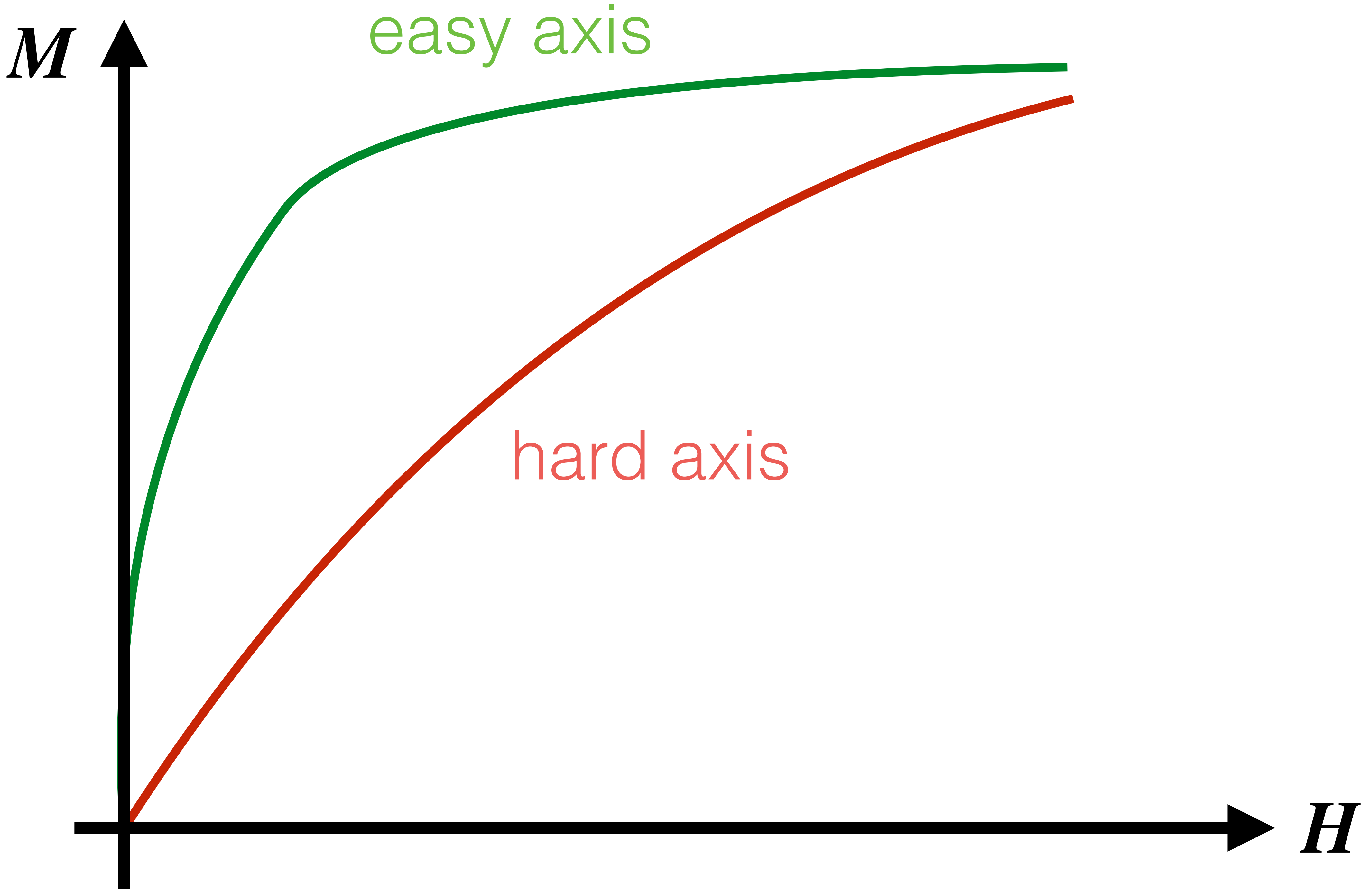
- hard to magnetise sample if field is applied along this direction
- magnetisation saturation is also reached but at relatively higher fields

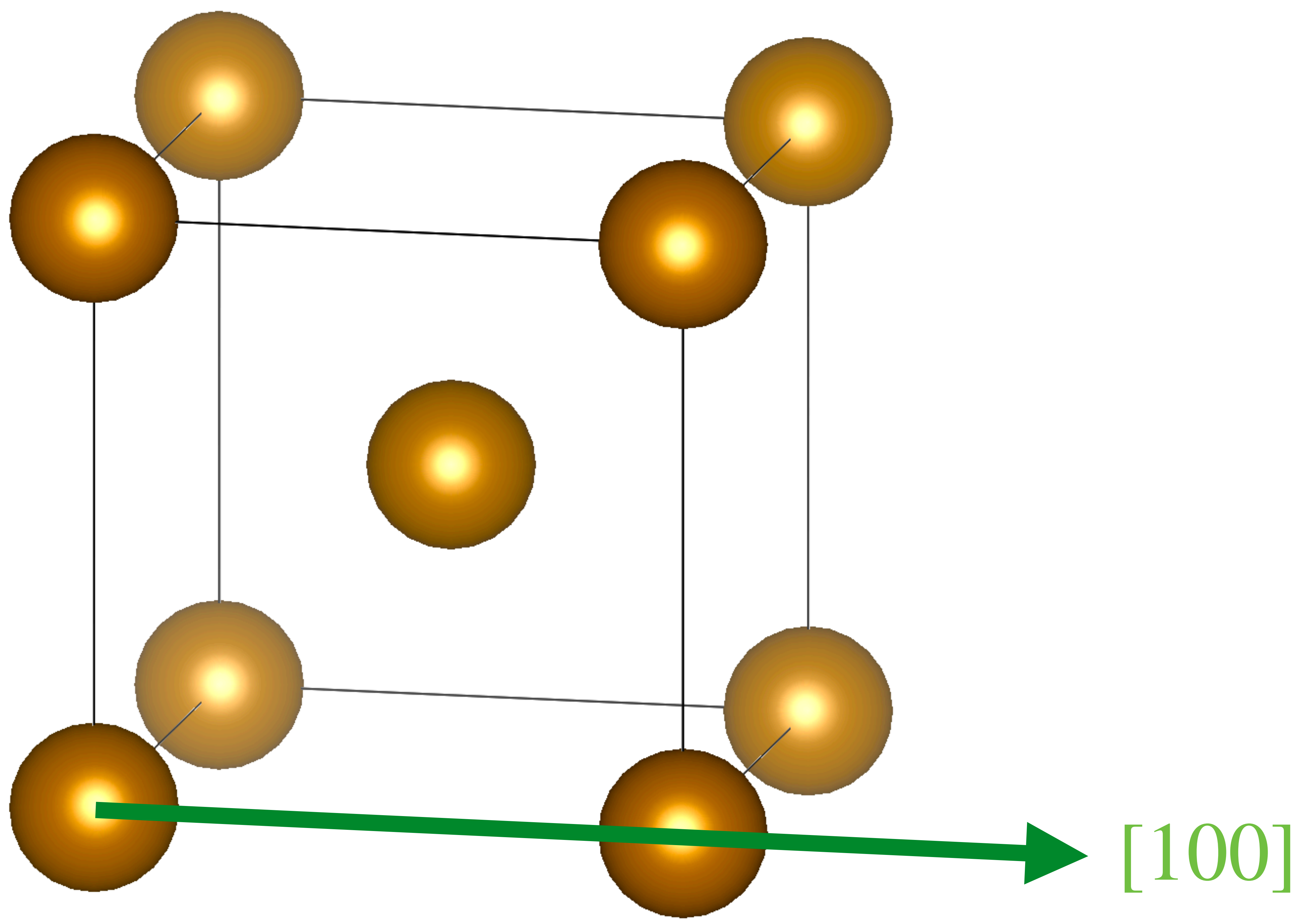
Anisotropy: magnetocrystalline anisotropy



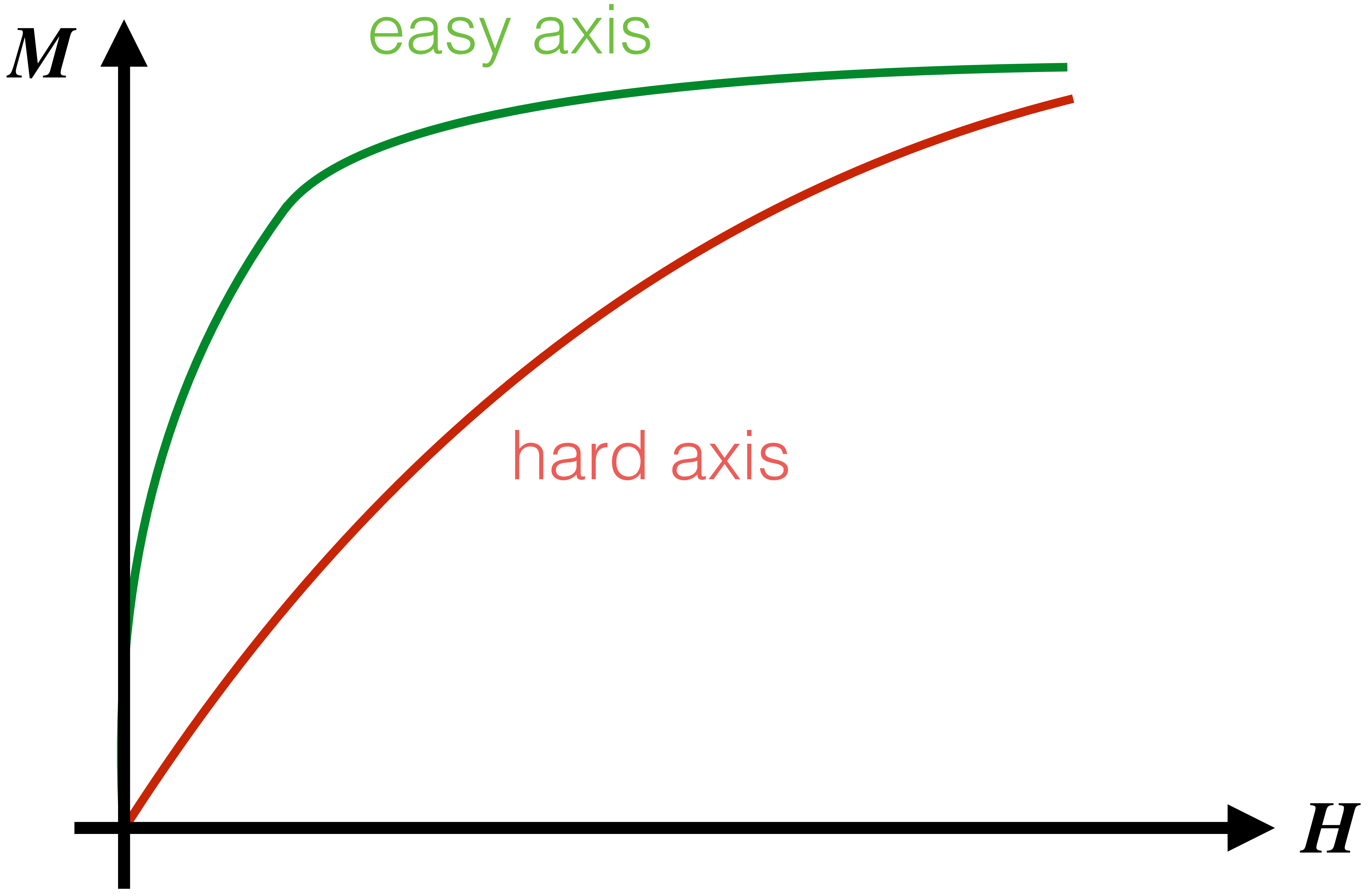
- α-iron
- Body-centred cubic (bcc)
- Conventional cell
- Stable below 912 °C
- Ferromagnetic ($T_c =$ 771 °C)

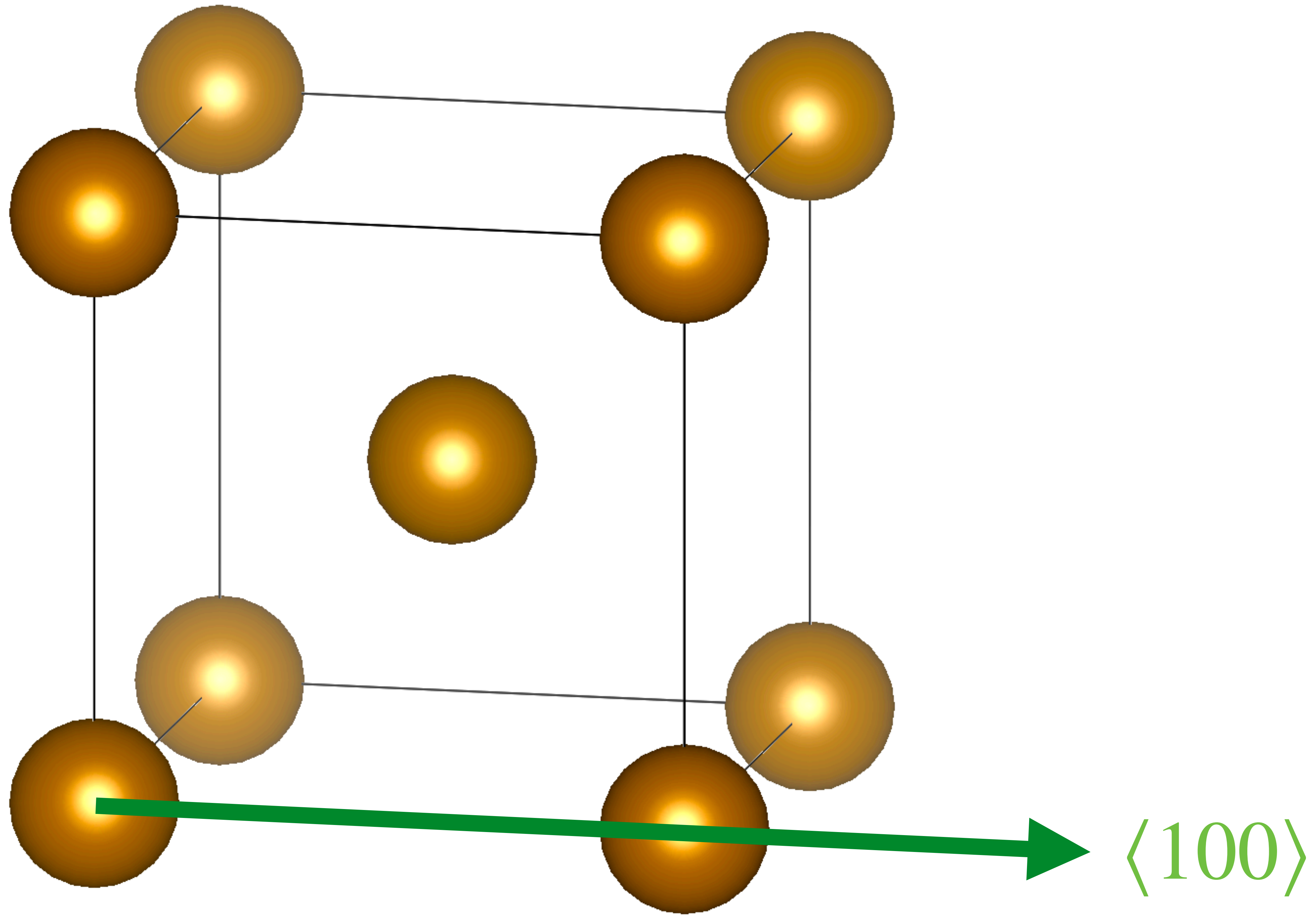
Anisotropy: magnetocrystalline anisotropy





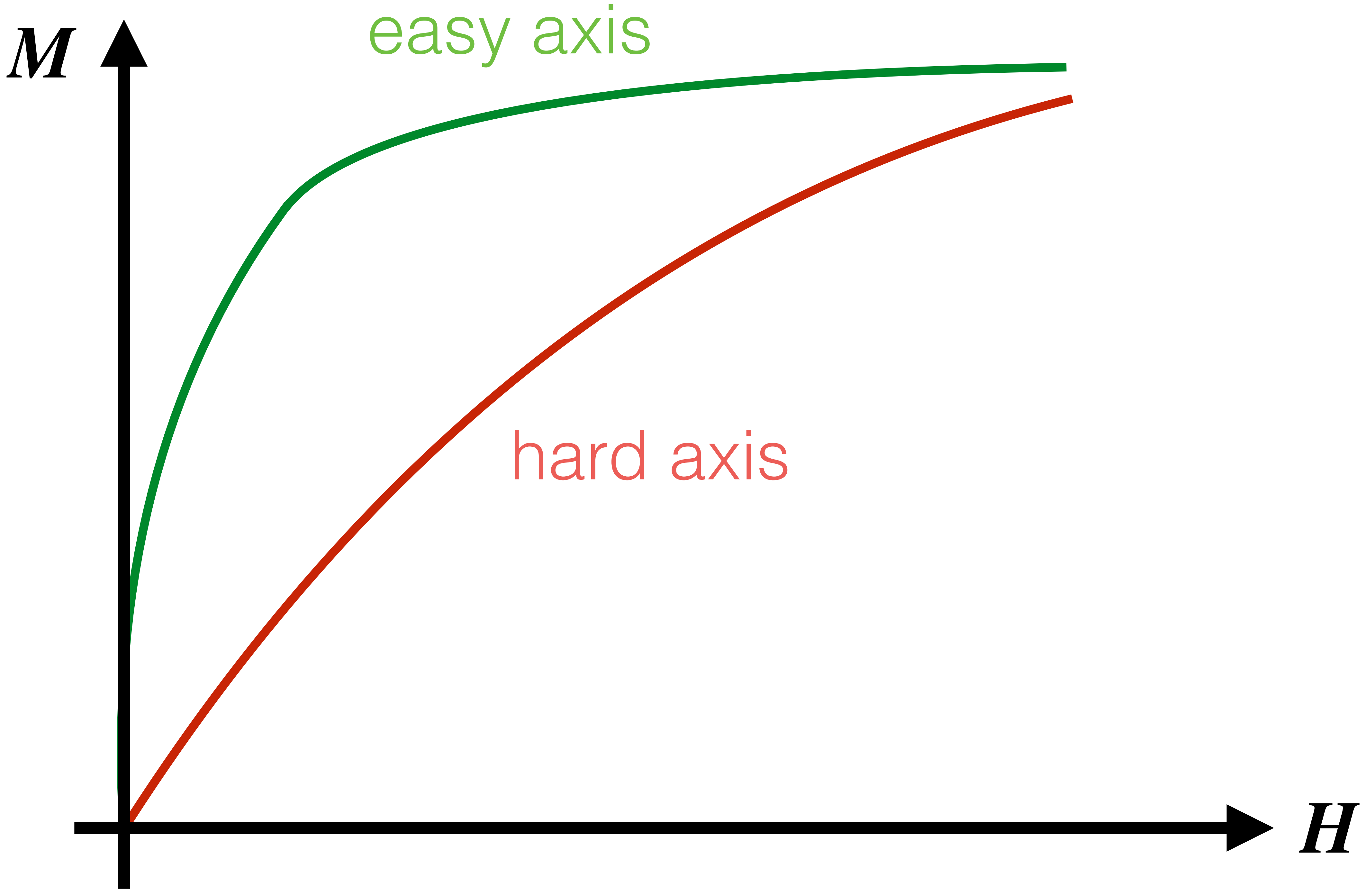
Anisotropy: magnetocrystalline anisotropy

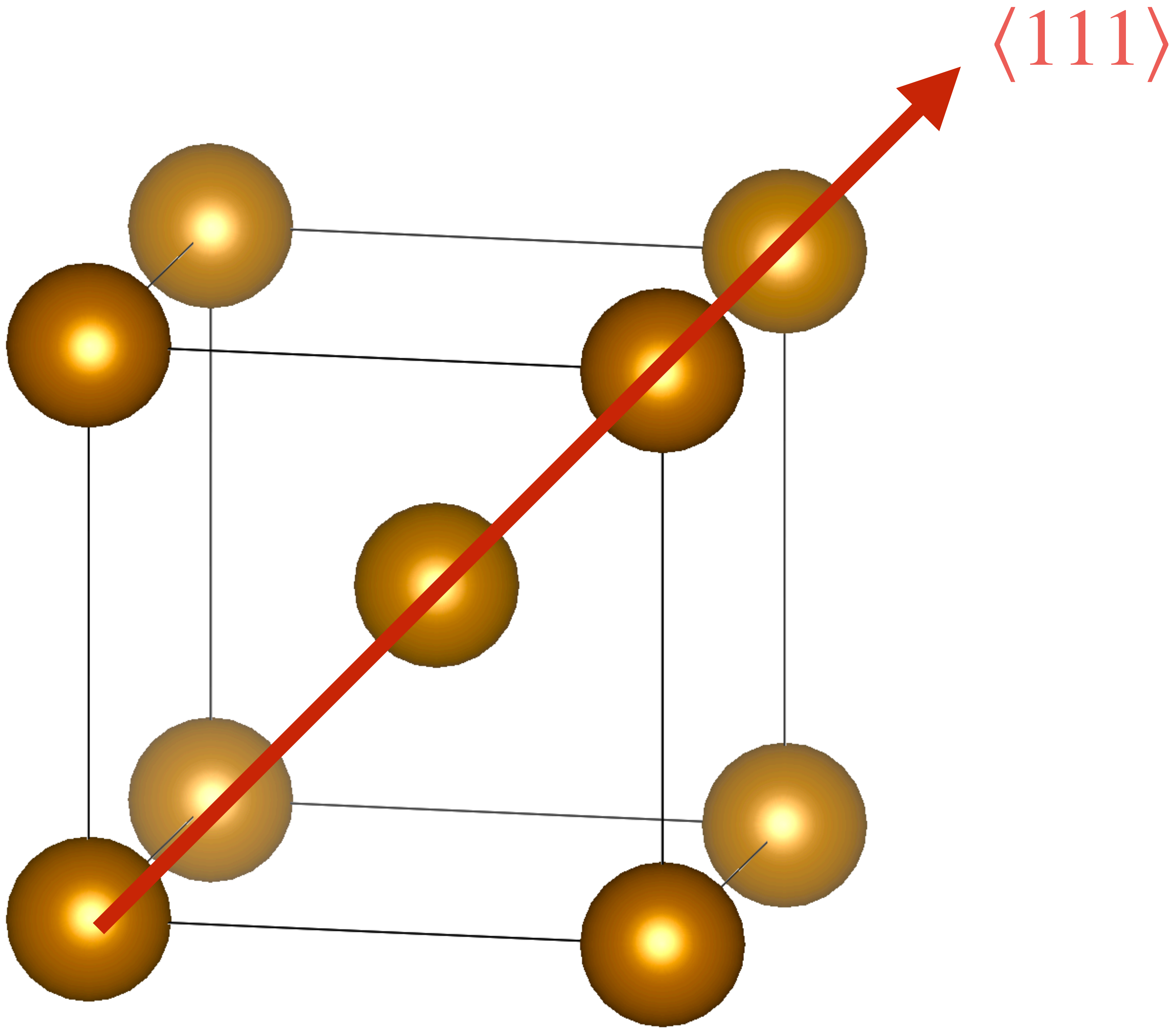




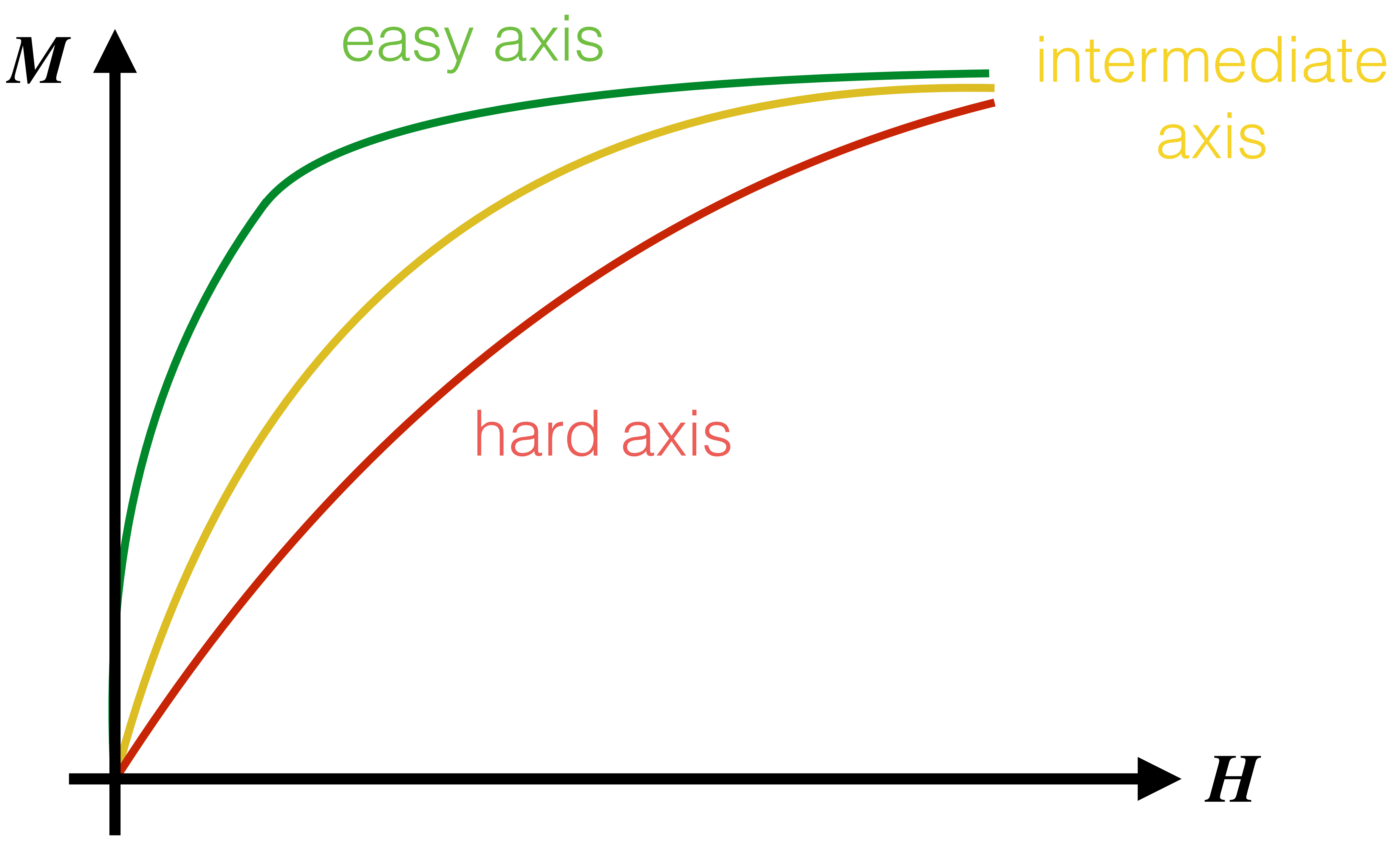
⟨100⟩: [100], [010], [001], $[\bar{1}00]$, $[0\bar{1}0]$, $[00\bar{1}]$

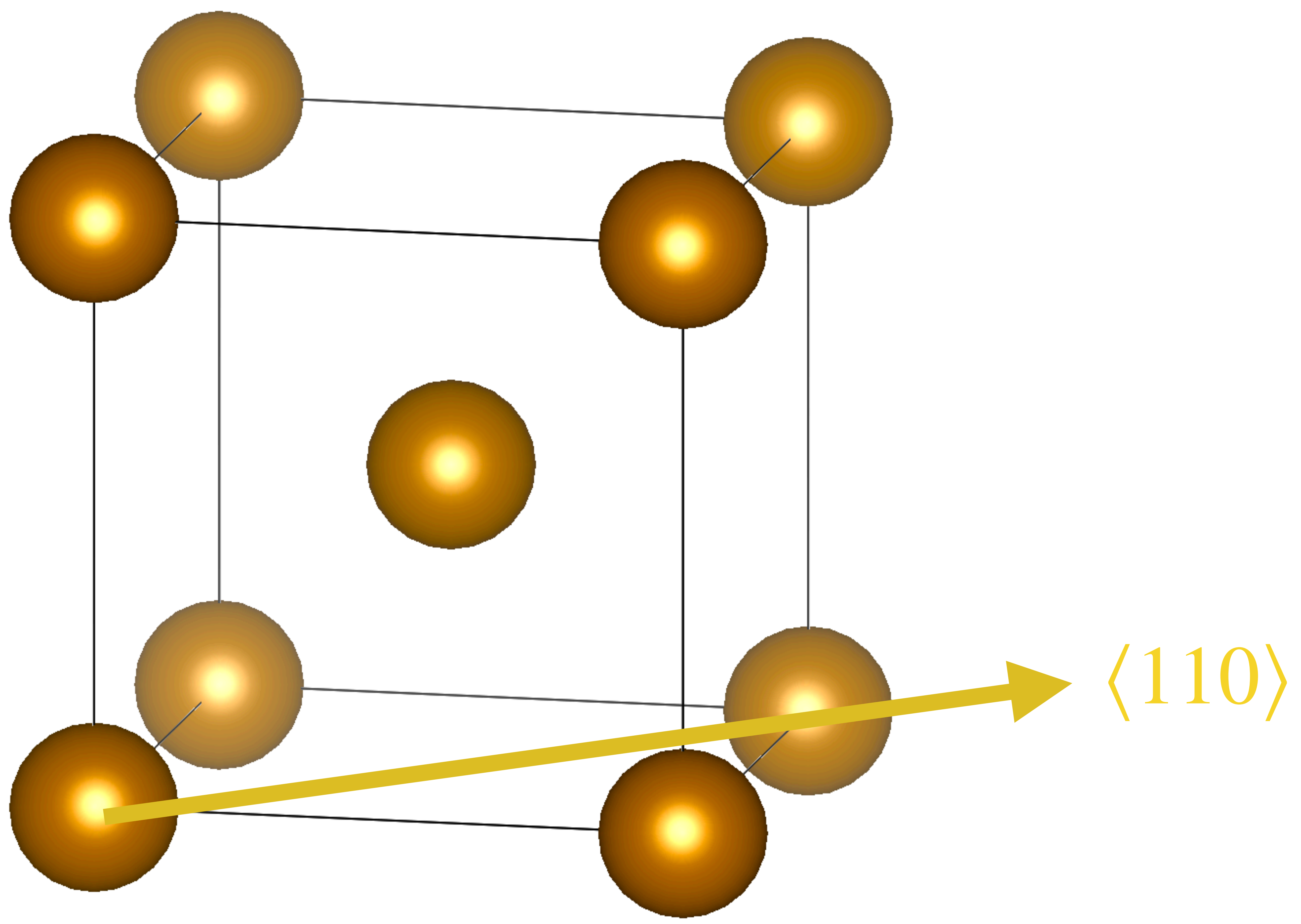
Anisotropy: magnetocrystalline anisotropy



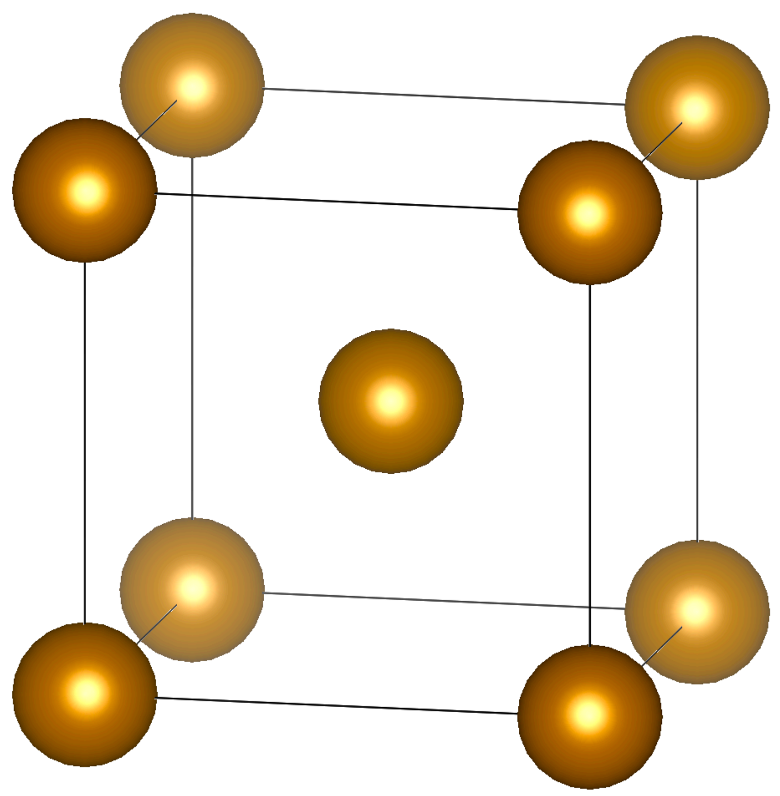


Anisotropy: magnetocrystalline anisotropy

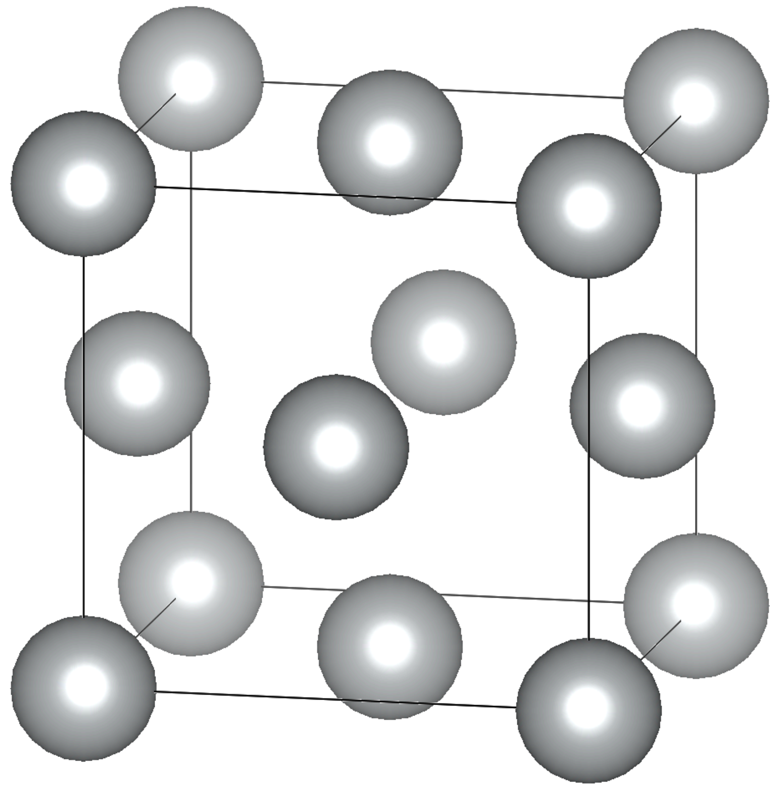




Anisotropy: magnetocrystalline anisotropy



bcc iron



fcc nickel

easy axis: $\langle 100 \rangle$

intermediate axis: $\langle 110 \rangle$

hard axis: $\langle 111 \rangle$

easy axis: $\langle 111 \rangle$

intermediate axis: $\langle 110 \rangle$

hard axis: $\langle 100 \rangle$

Anisotropy: magnetocrystalline anisotropy

- Spin-orbit interaction:

$$\boldsymbol{L} \cdot \boldsymbol{S}$$

$\boldsymbol{L}$: orbital angular momentum

$\boldsymbol{S}$: spin angular momentum

- Relativistic effect (Dirac equation)

- Magnitude increases with atomic number

Anisotropy: magnetocrystalline anisotropy

- Spin-orbit interaction:

$$\boldsymbol{L} \cdot \boldsymbol{S}$$

$\boldsymbol{L}$: orbital angular momentum

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- Relativistic effect (Dirac equation)

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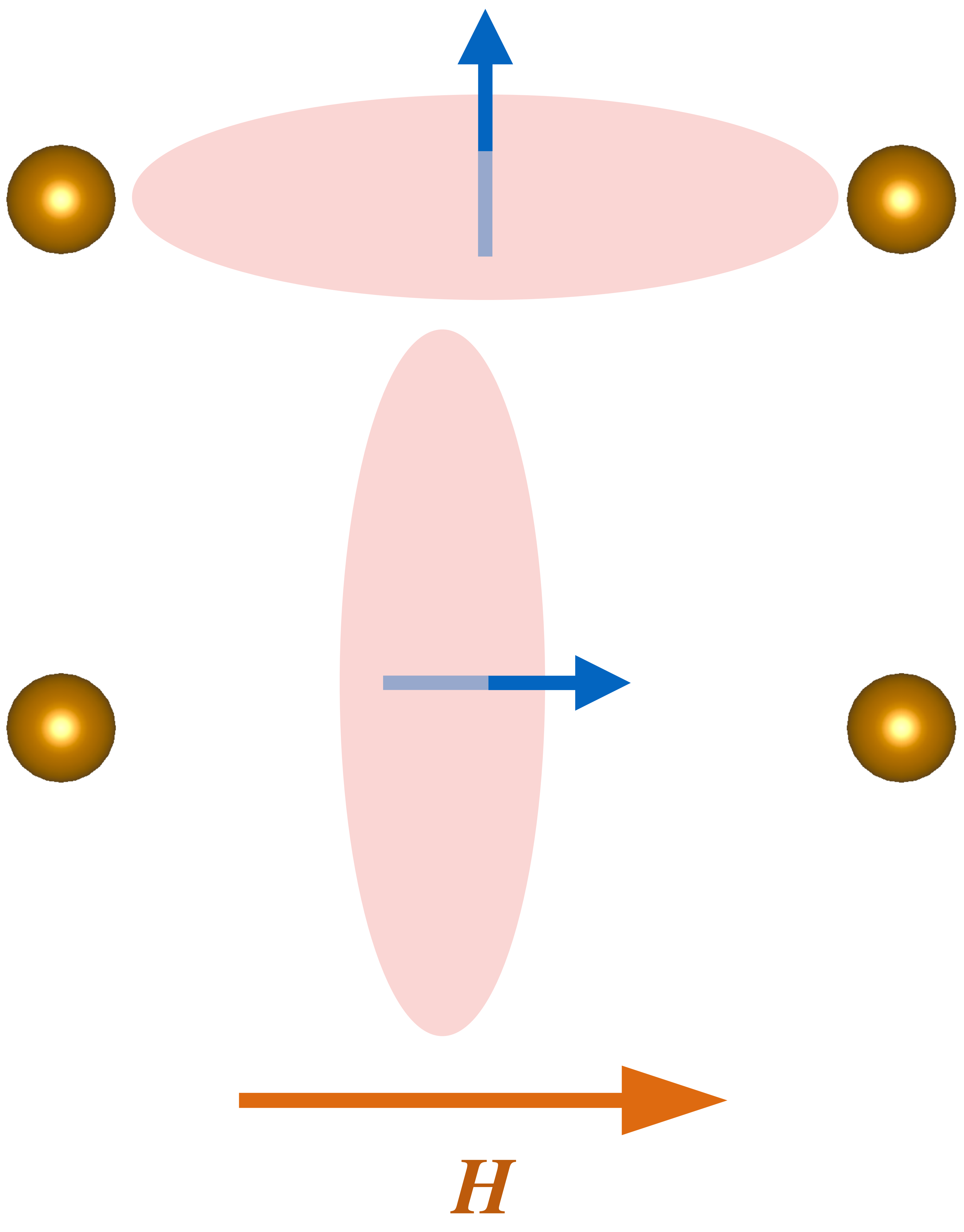
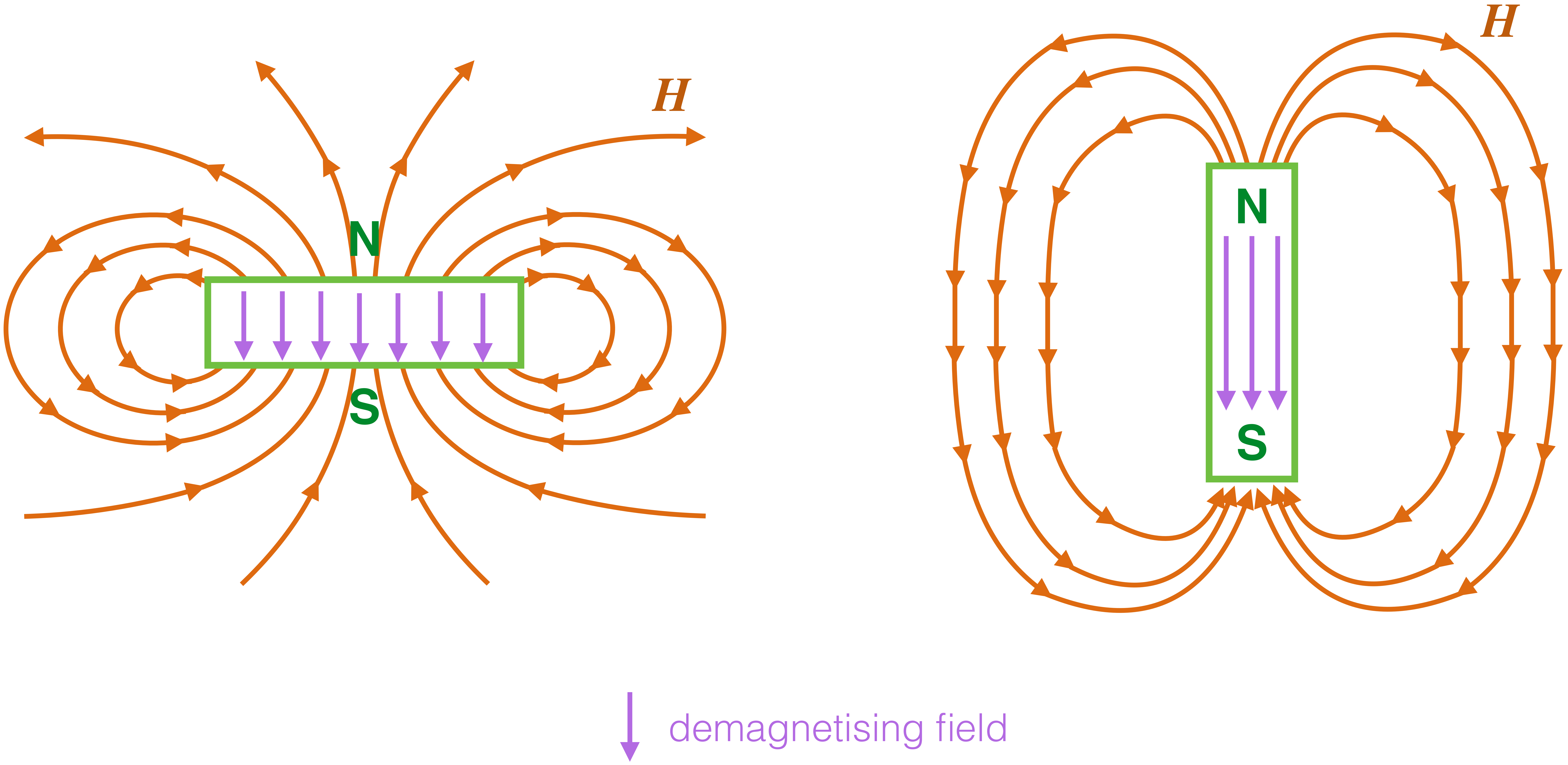
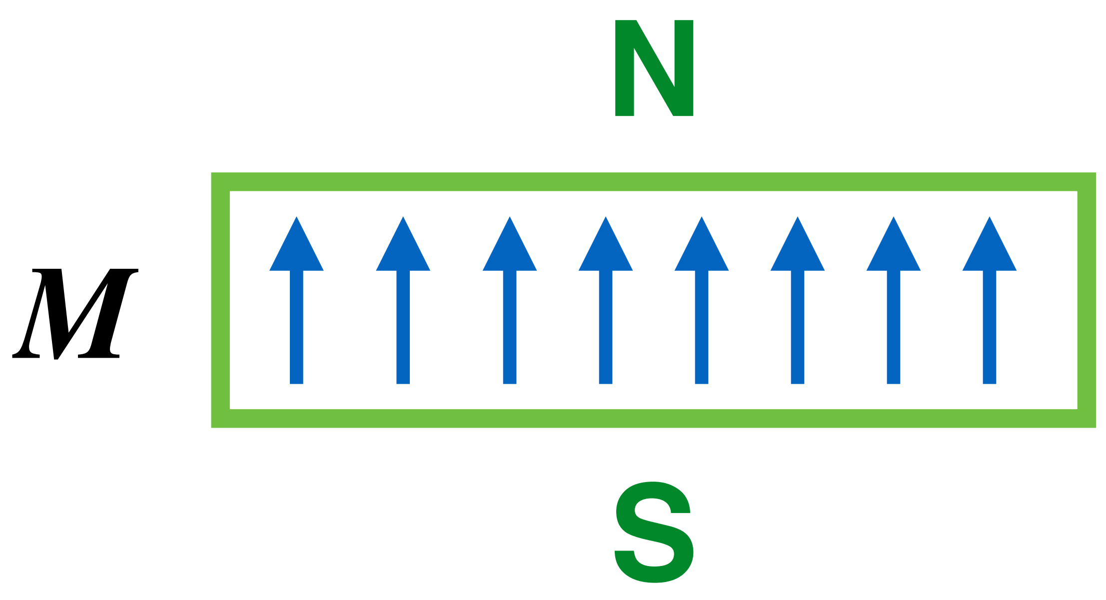


Anisotropy: shape anisotropy

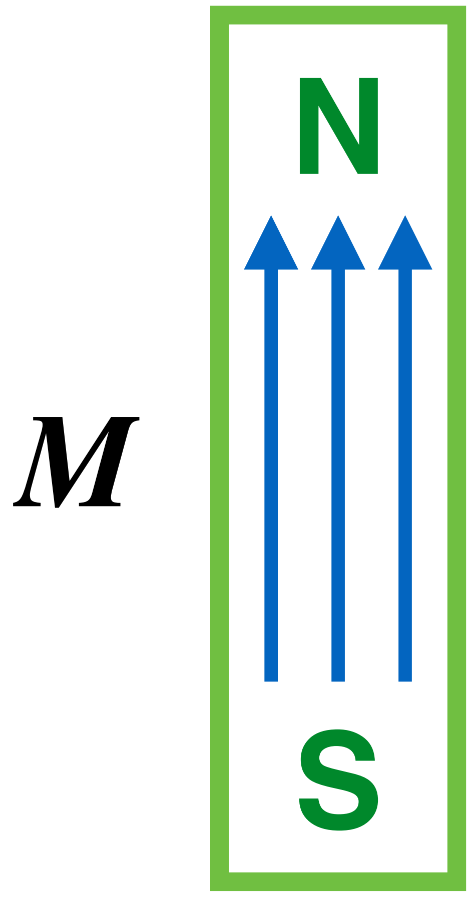


Anisotropy: shape anisotropy

hard shape

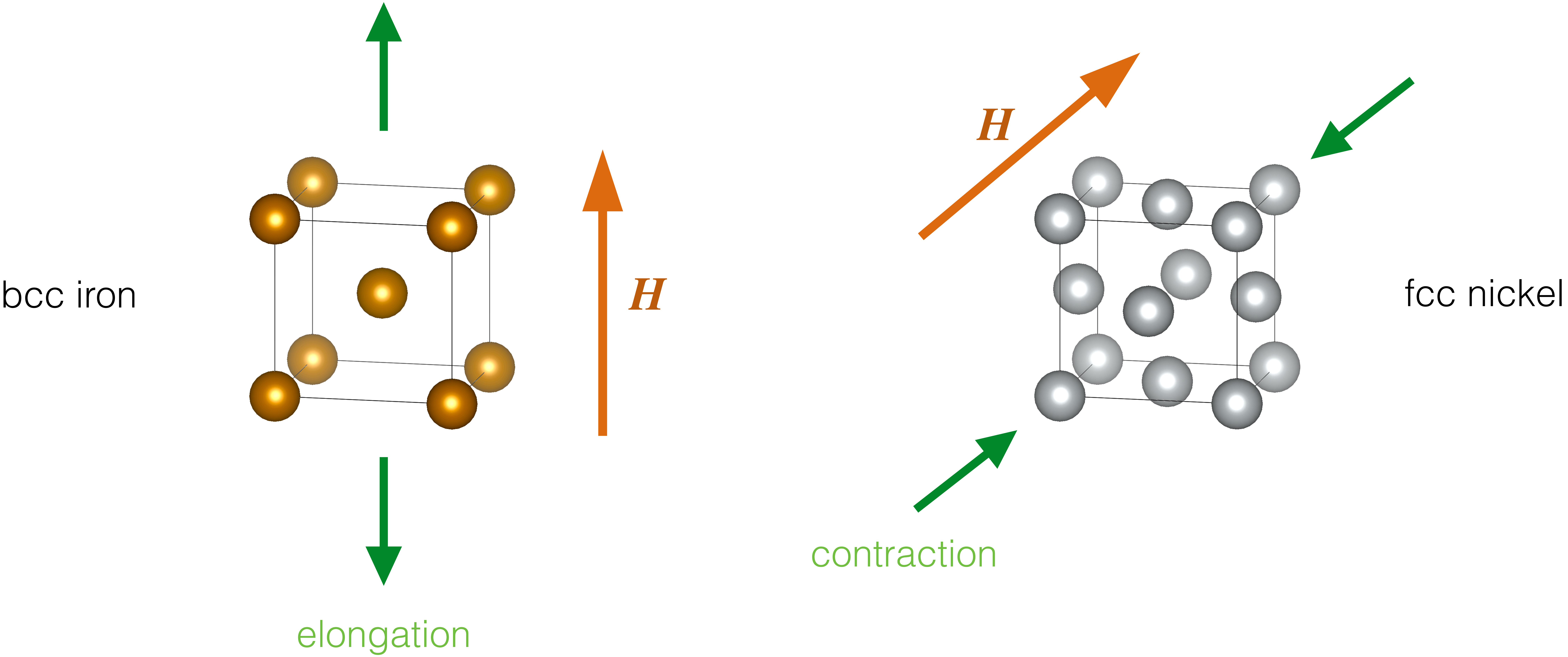


easy shape

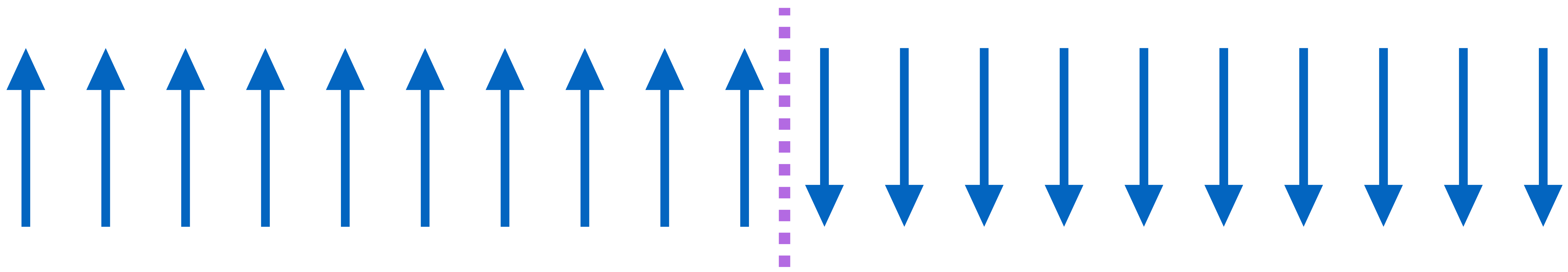


Magnetostriction

- Magnetostriction: change in shape when a material is magnetised



Domain walls

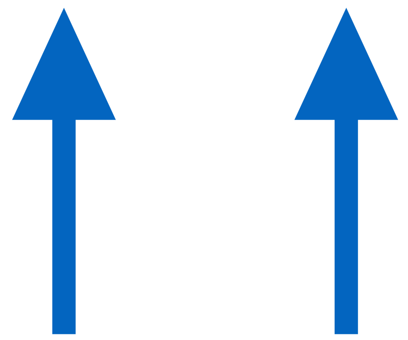


Domain wall size

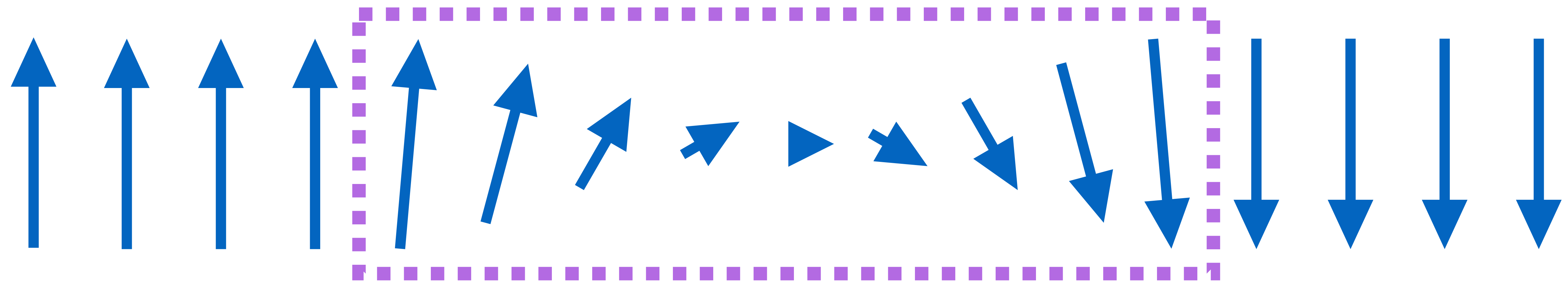
exchange interaction

different spatial part

×

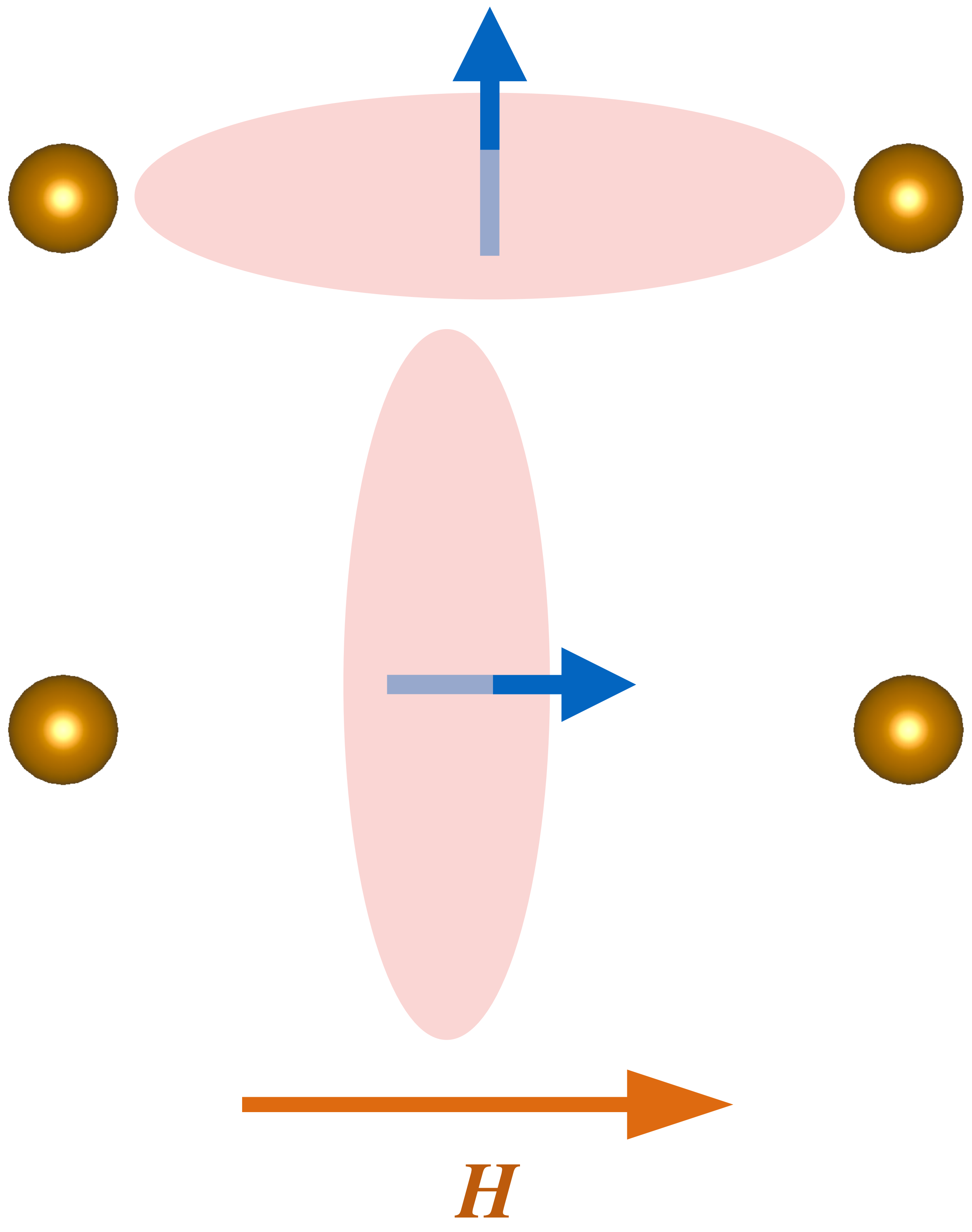


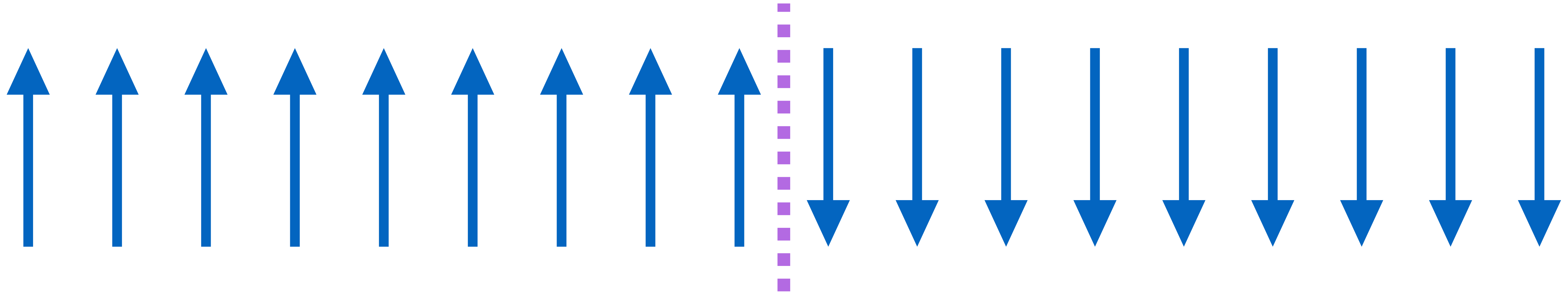
weak Coulomb repulsion



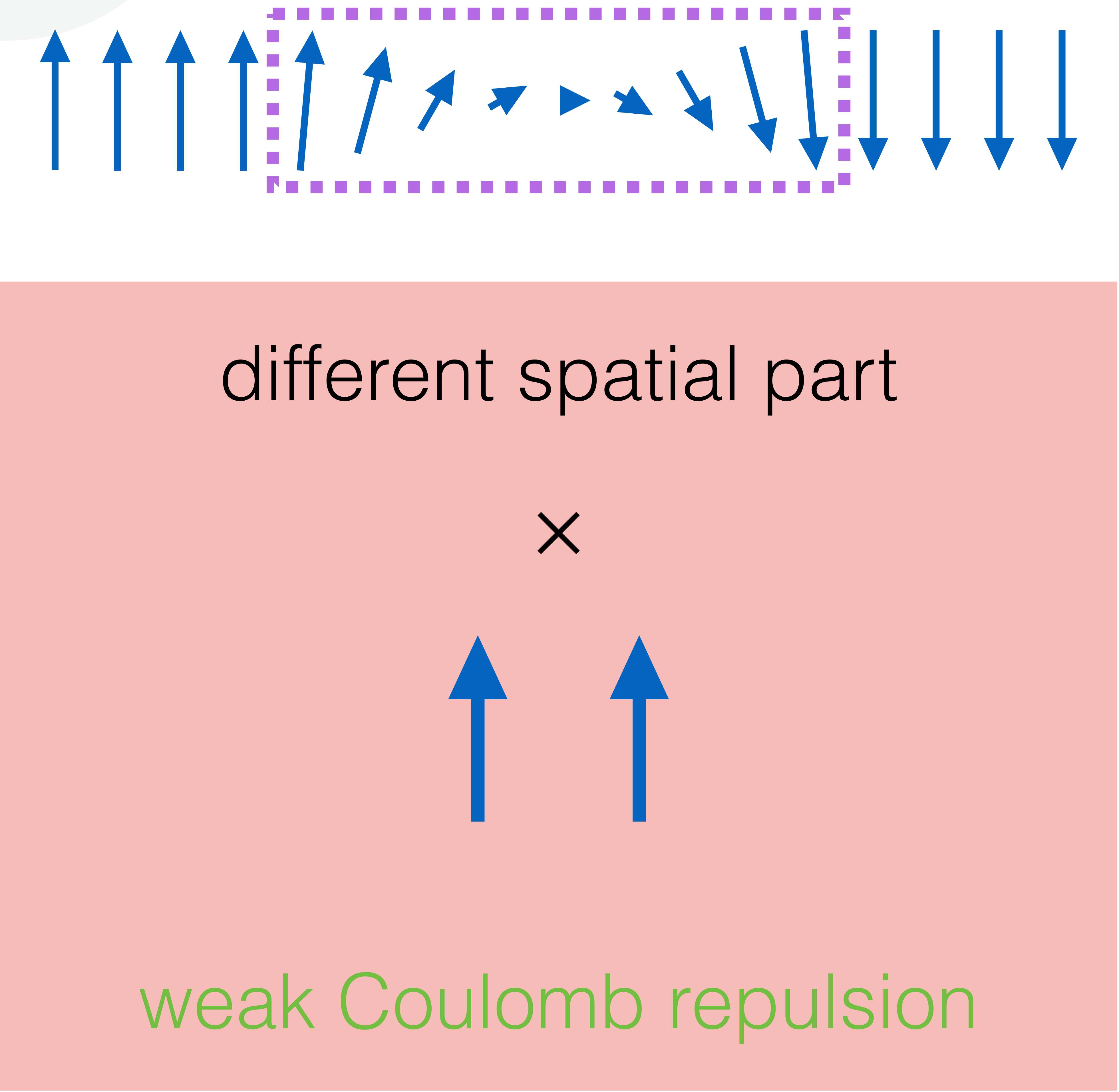
Domain wall size

magnetocrystalline
anisotropy

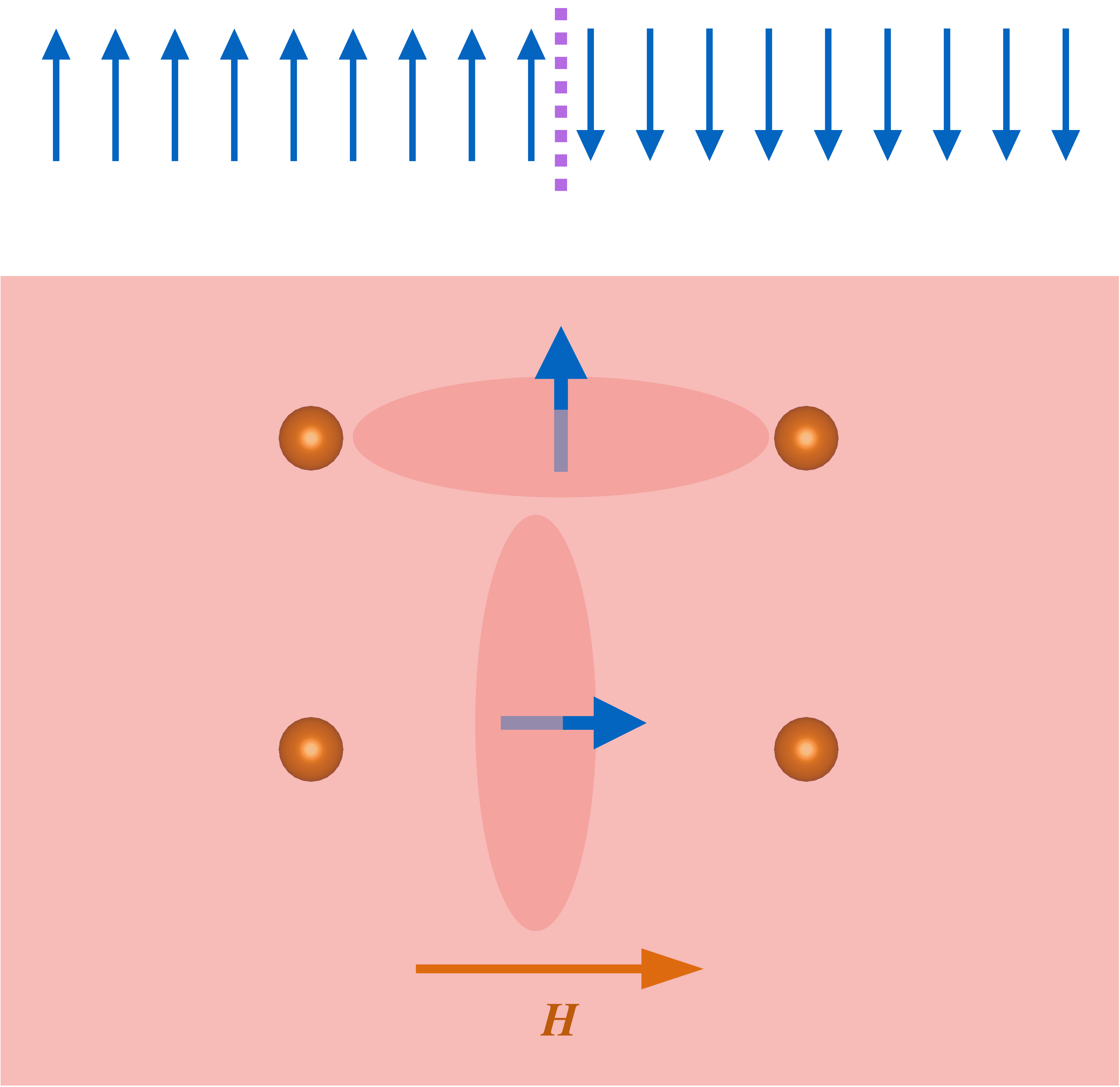




Domain wall size



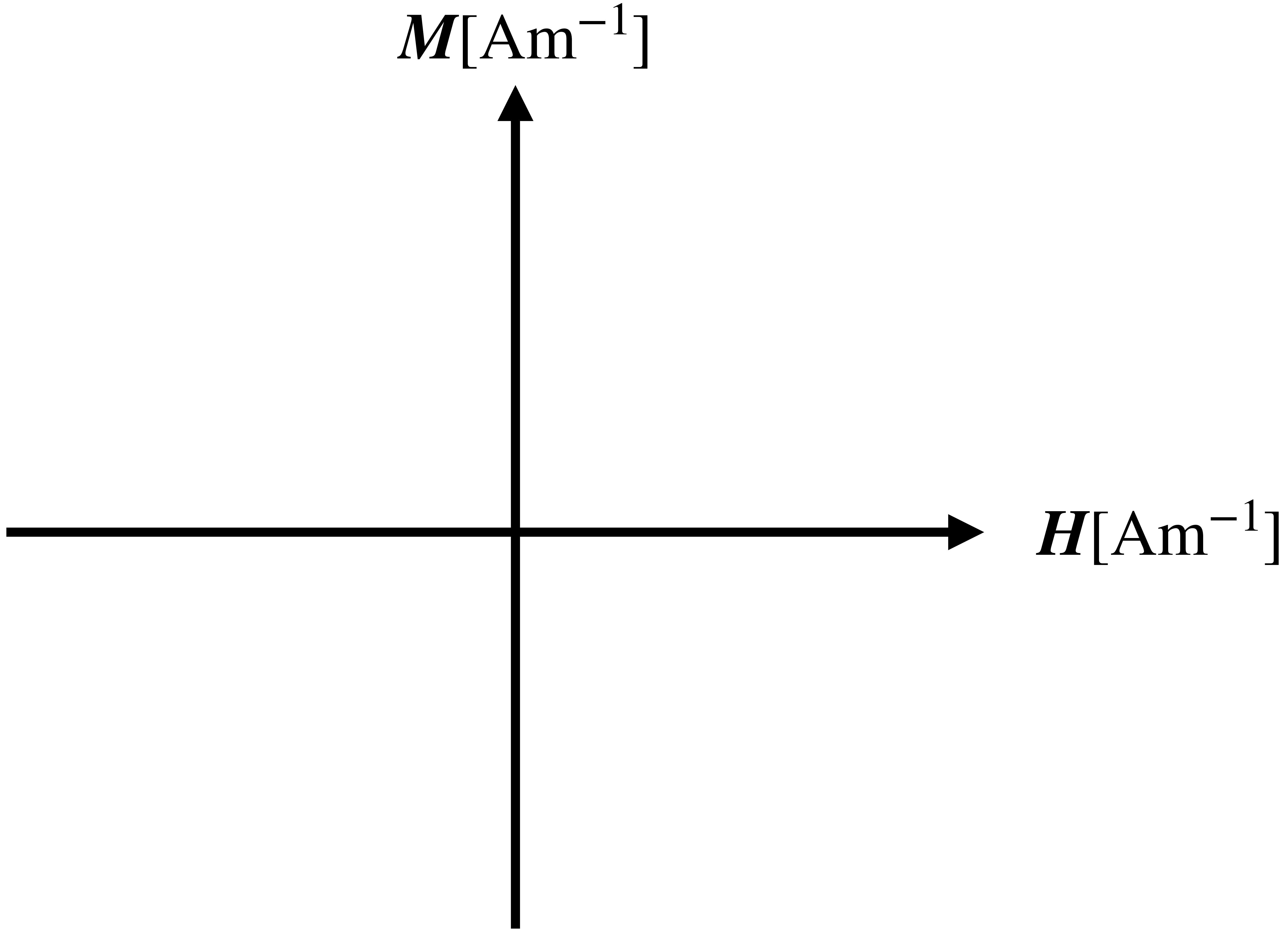
vs.



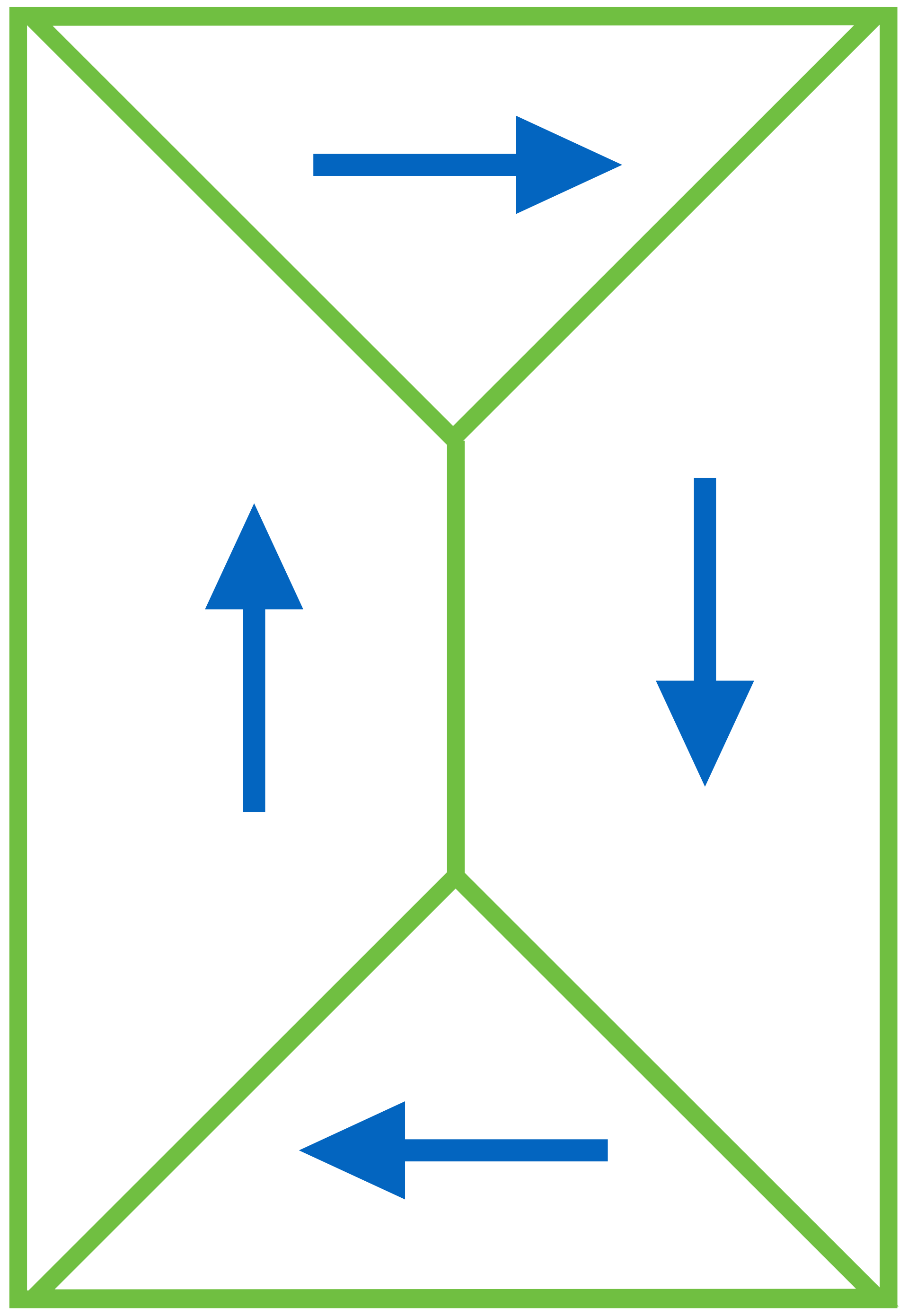
exchange interaction

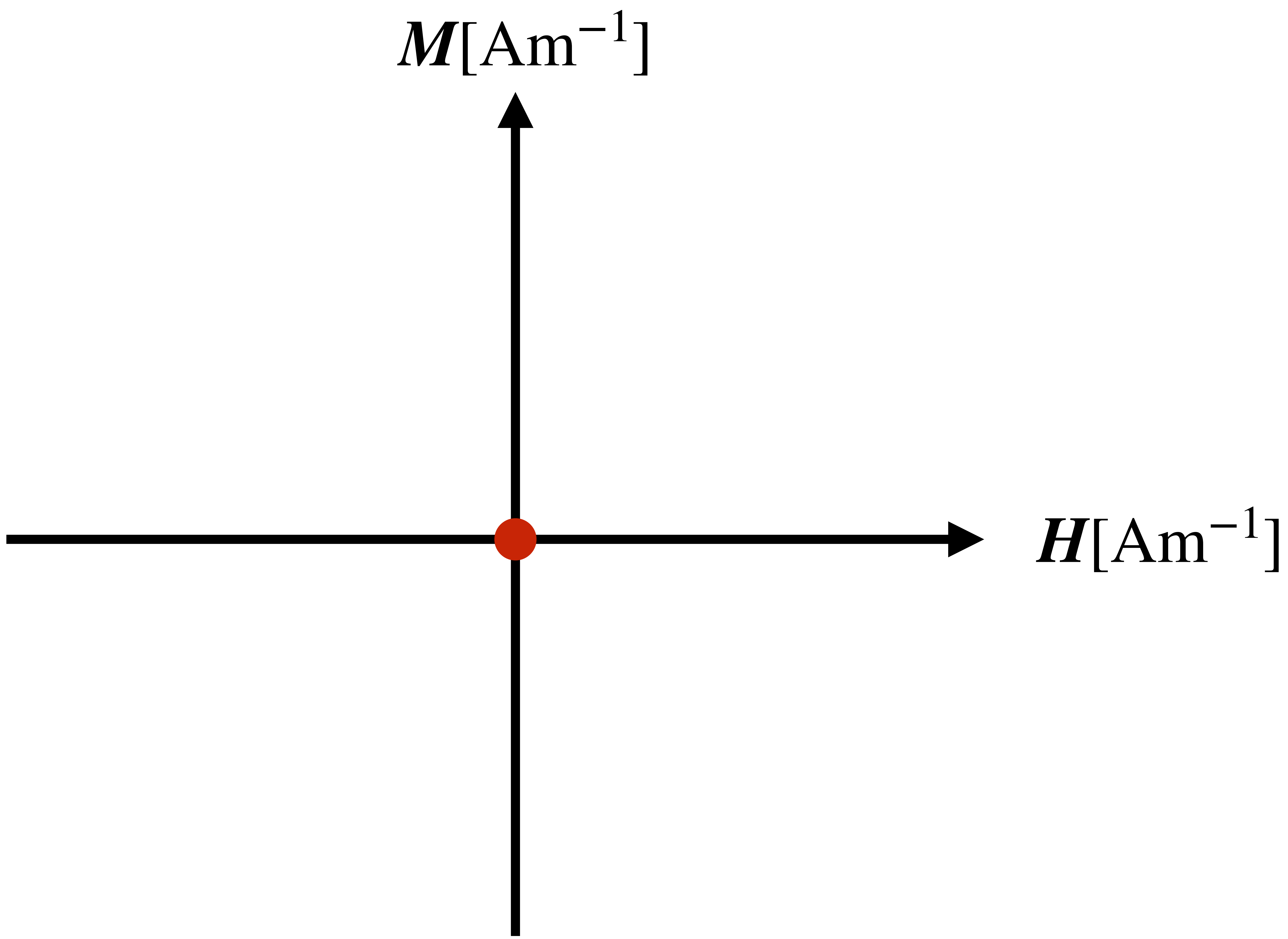
magnetocrystalline anisotropy

Hysteresis loop



Hysteresis loop





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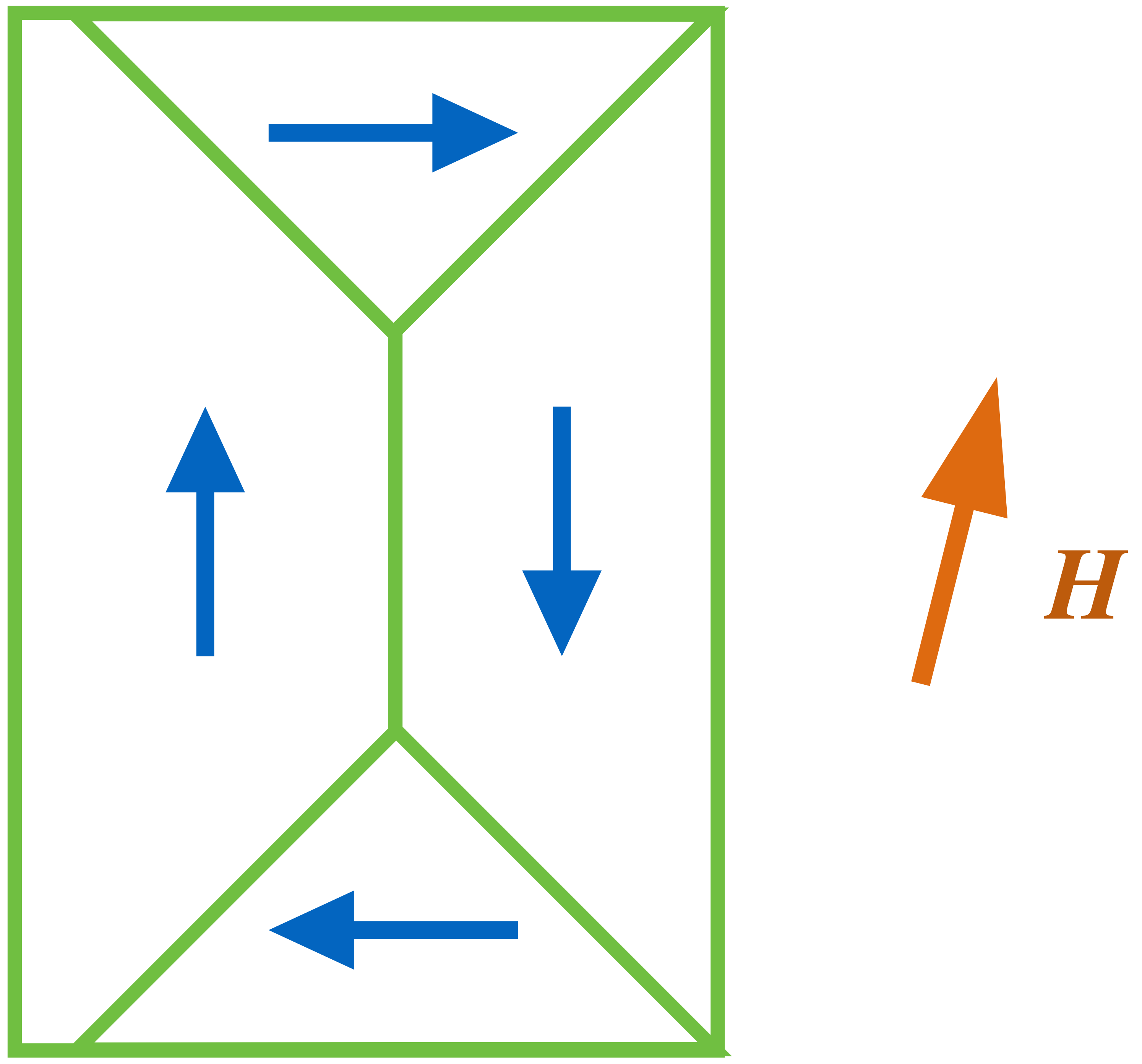
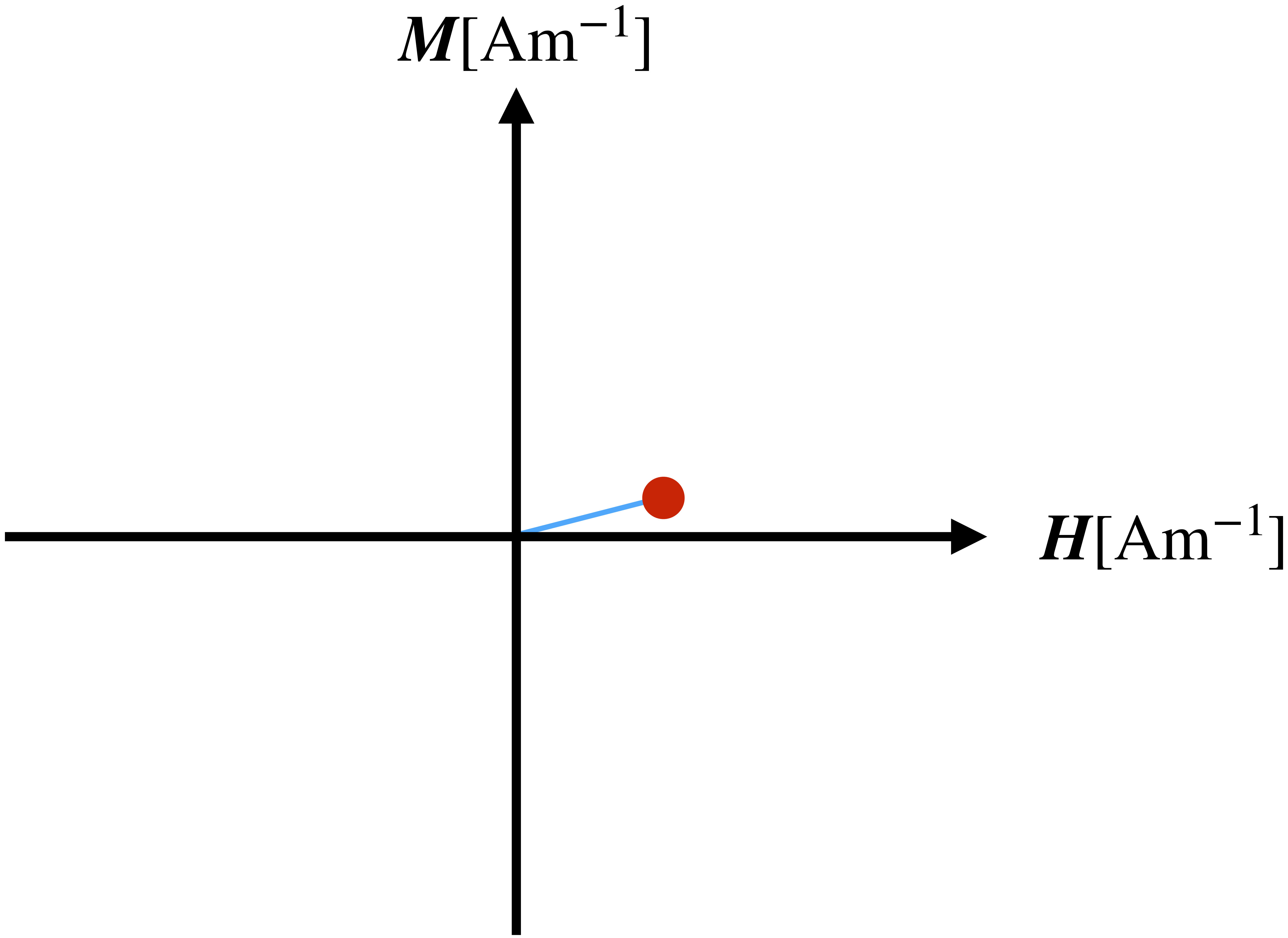
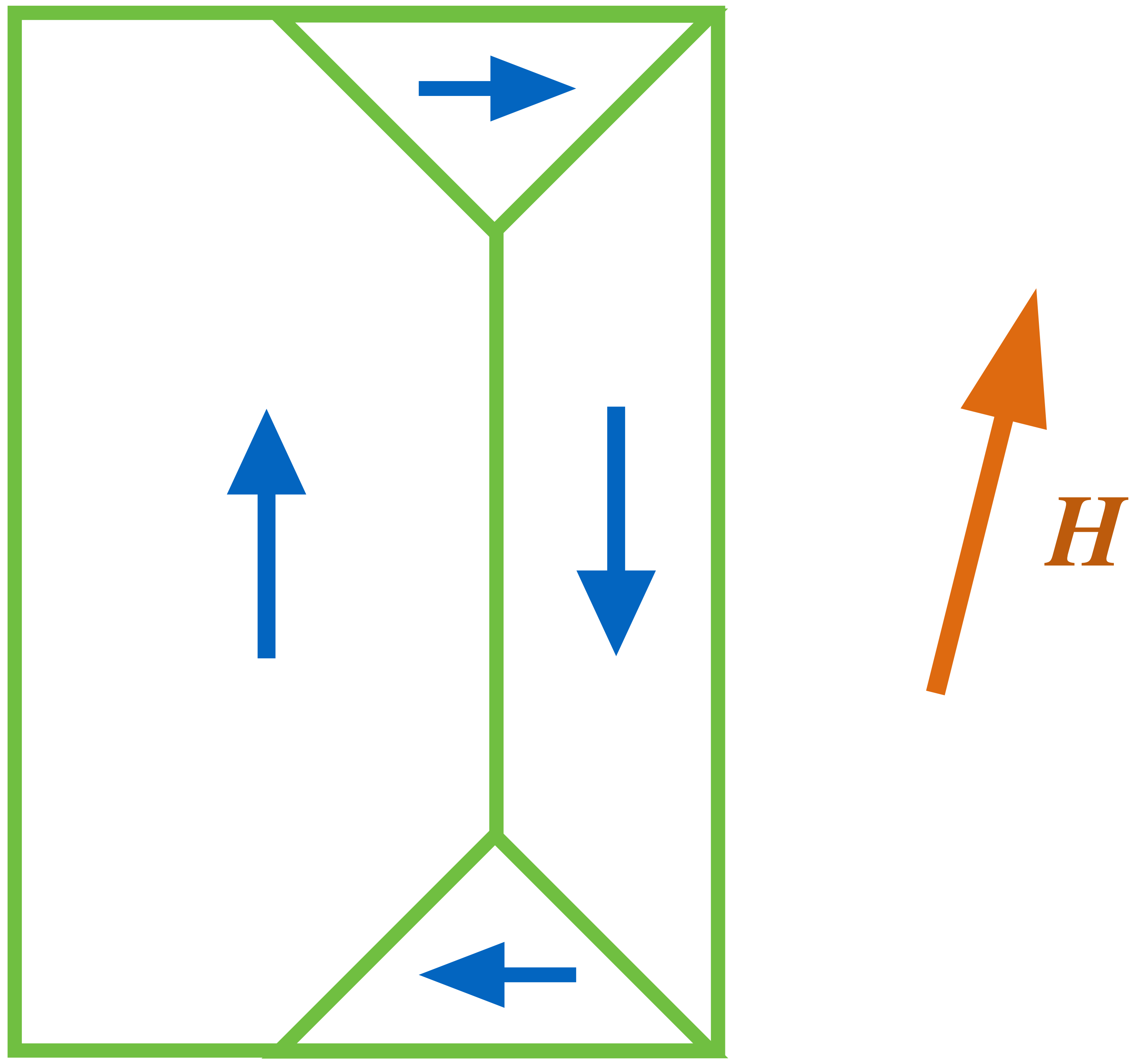
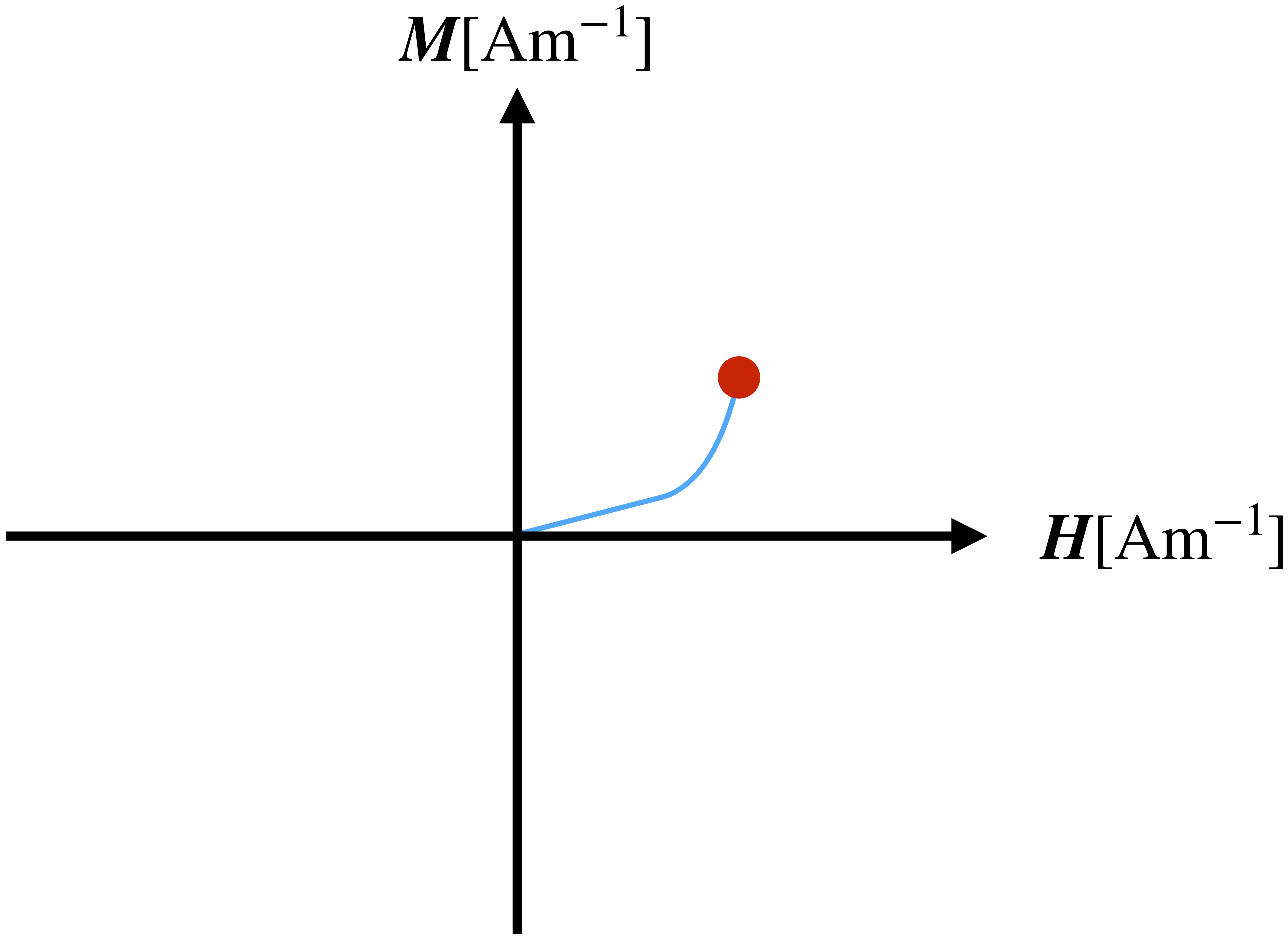


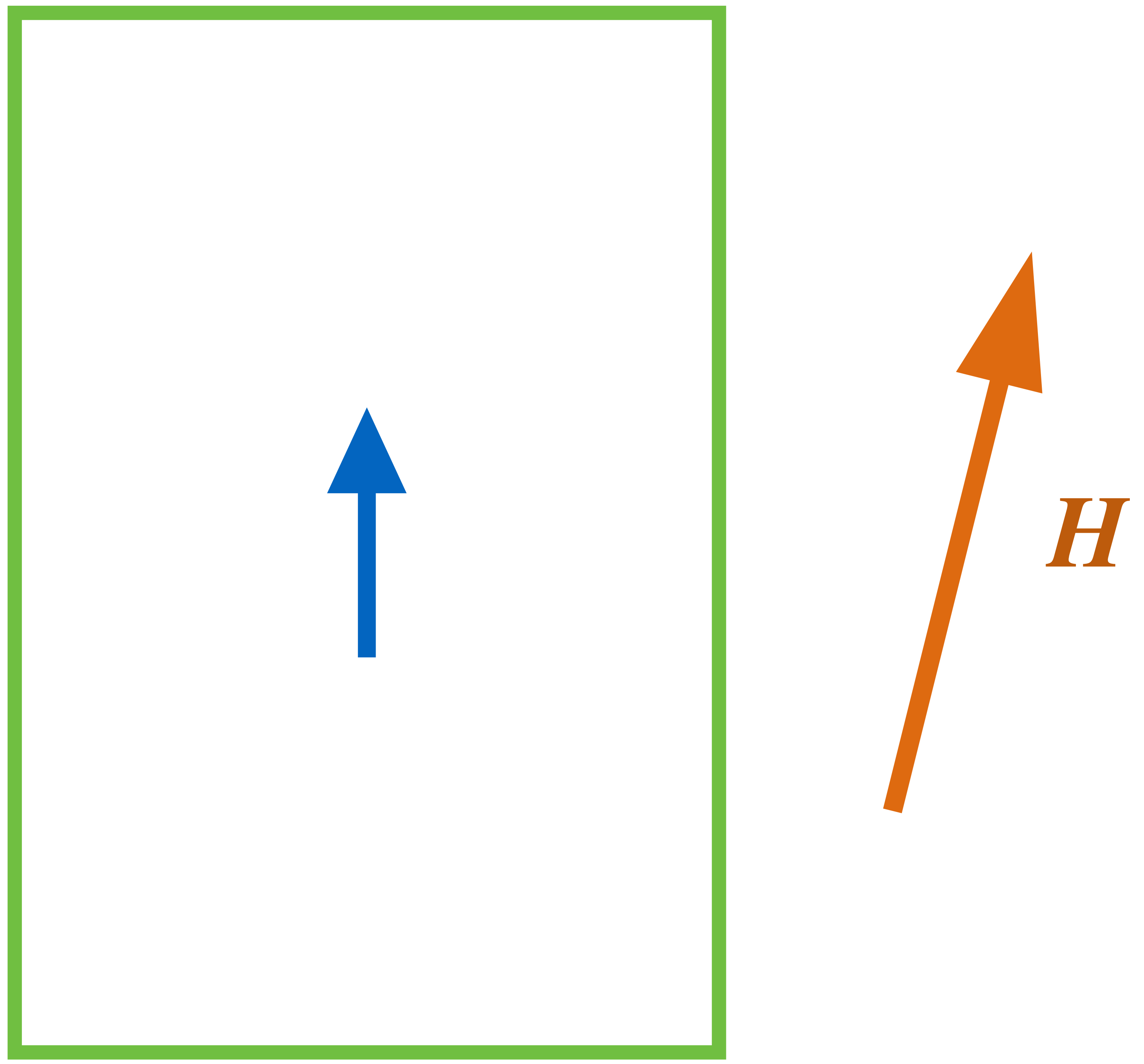


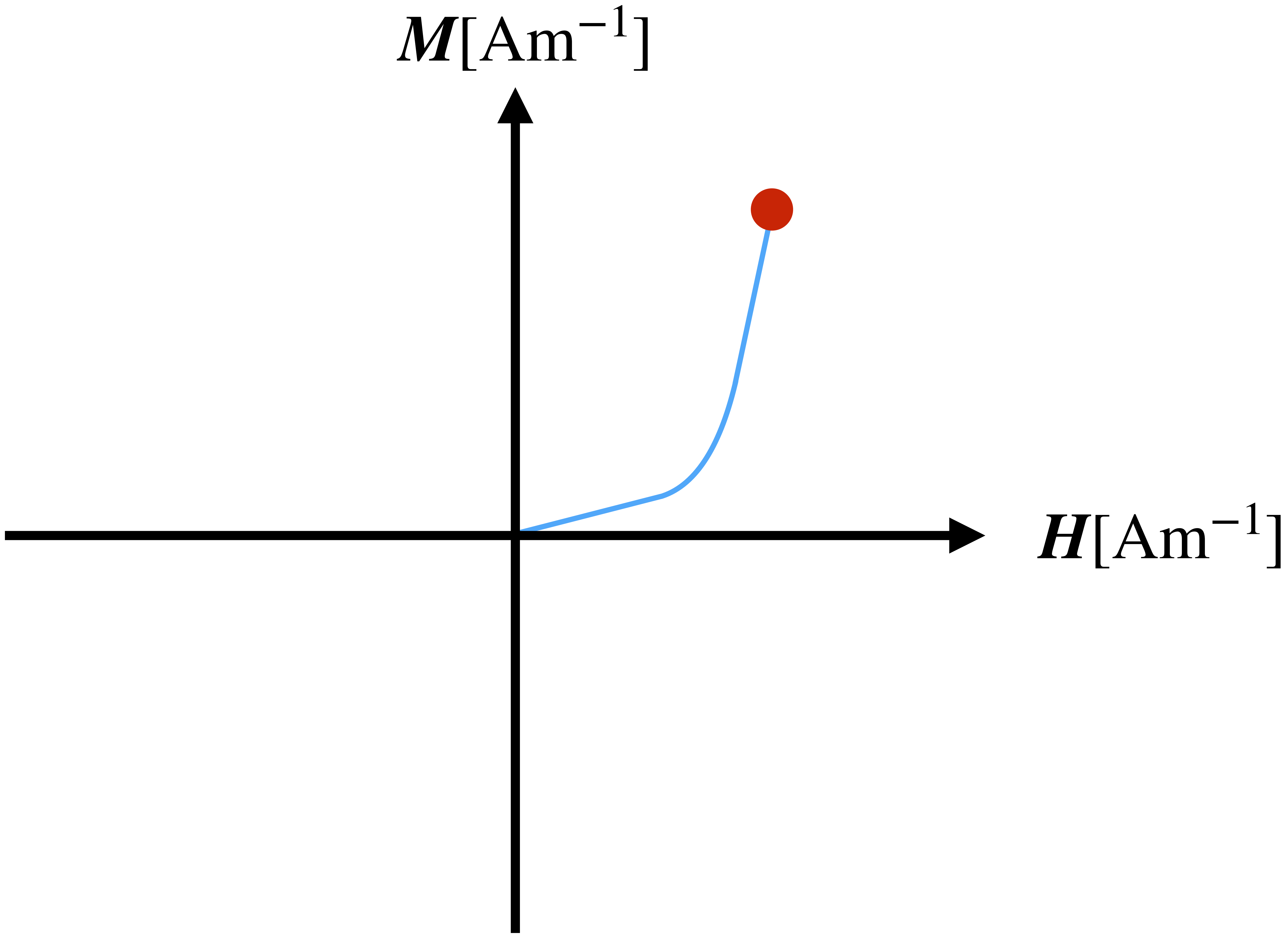
Hysteresis loop





Hysteresis loop





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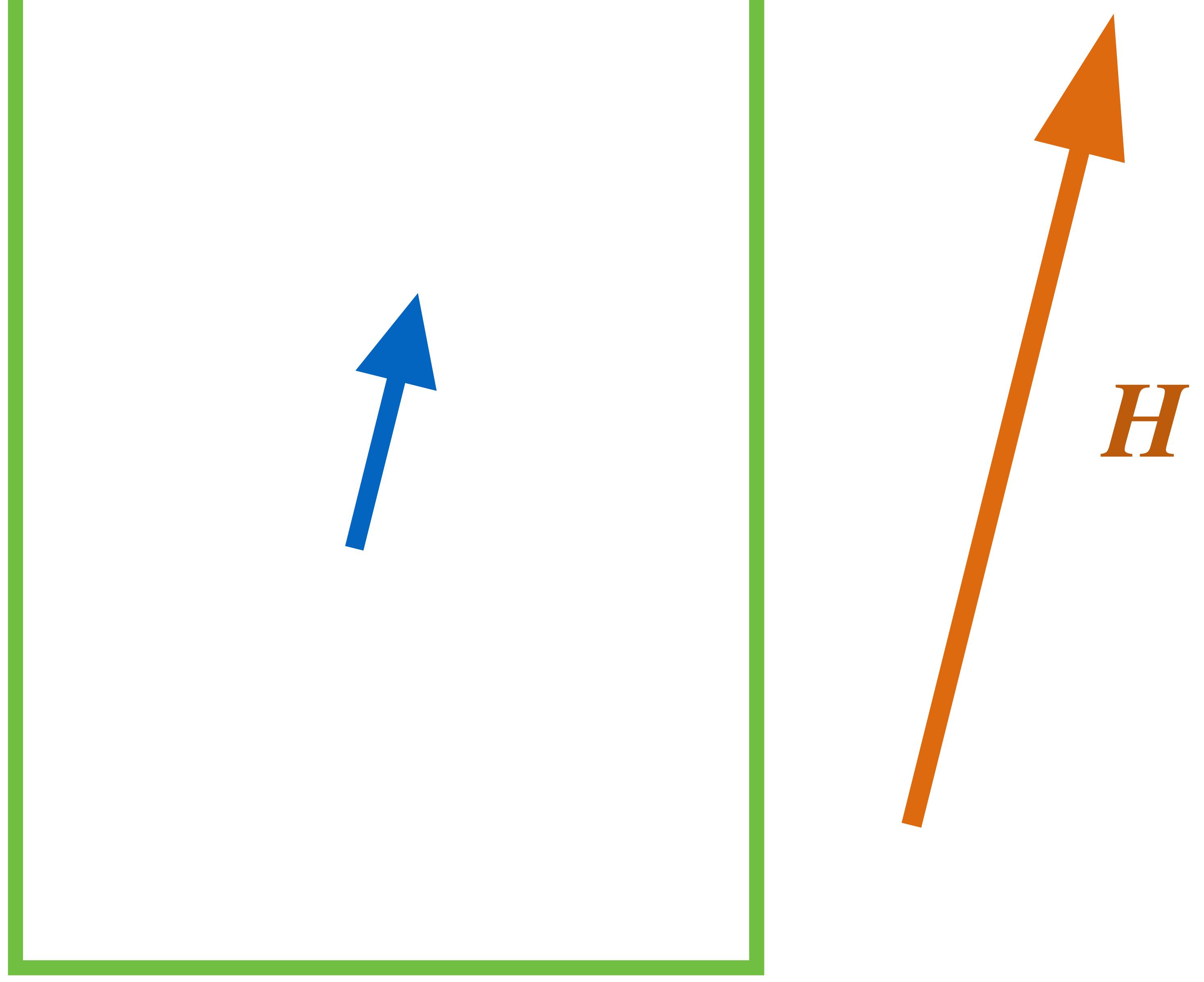
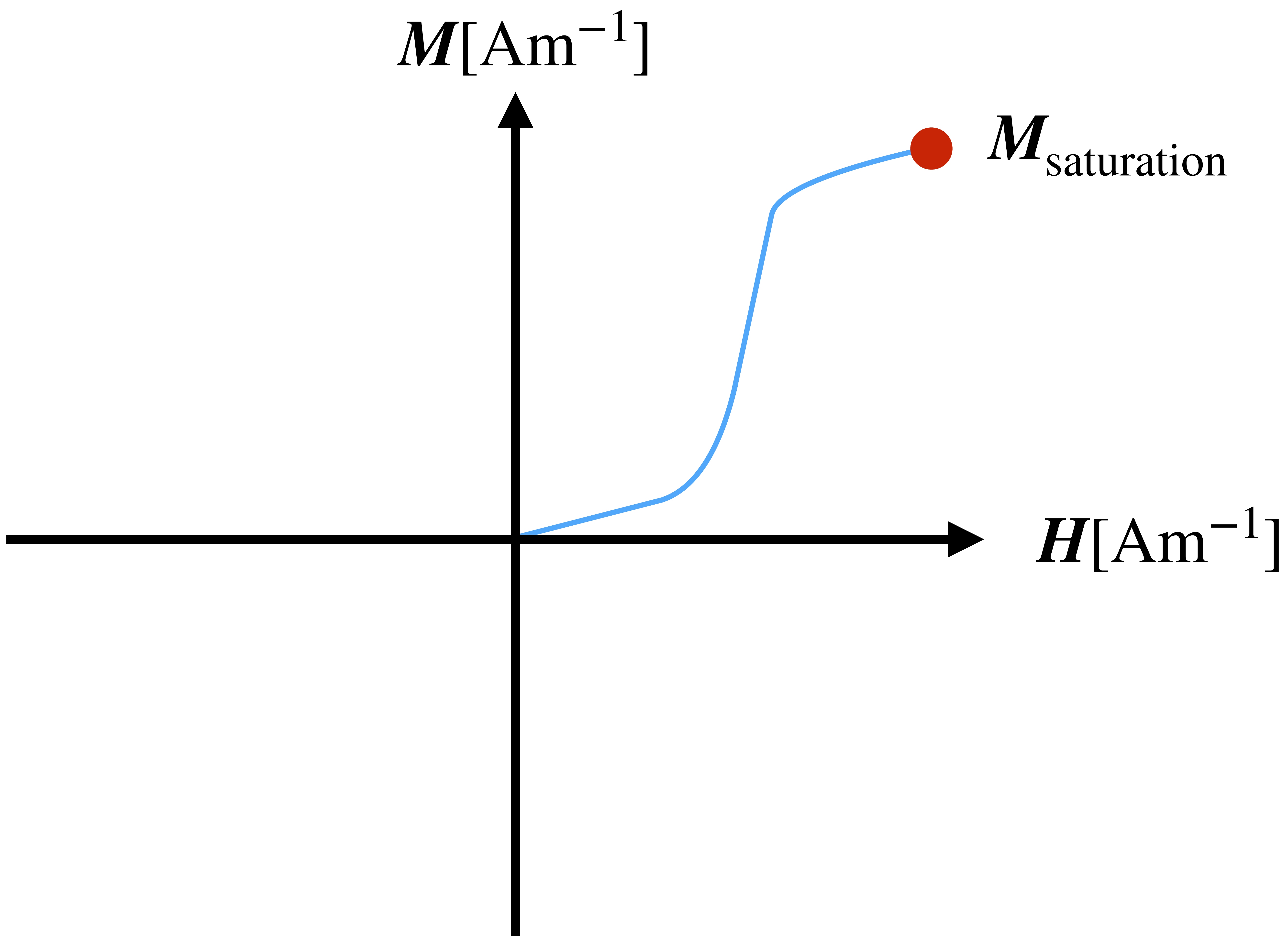
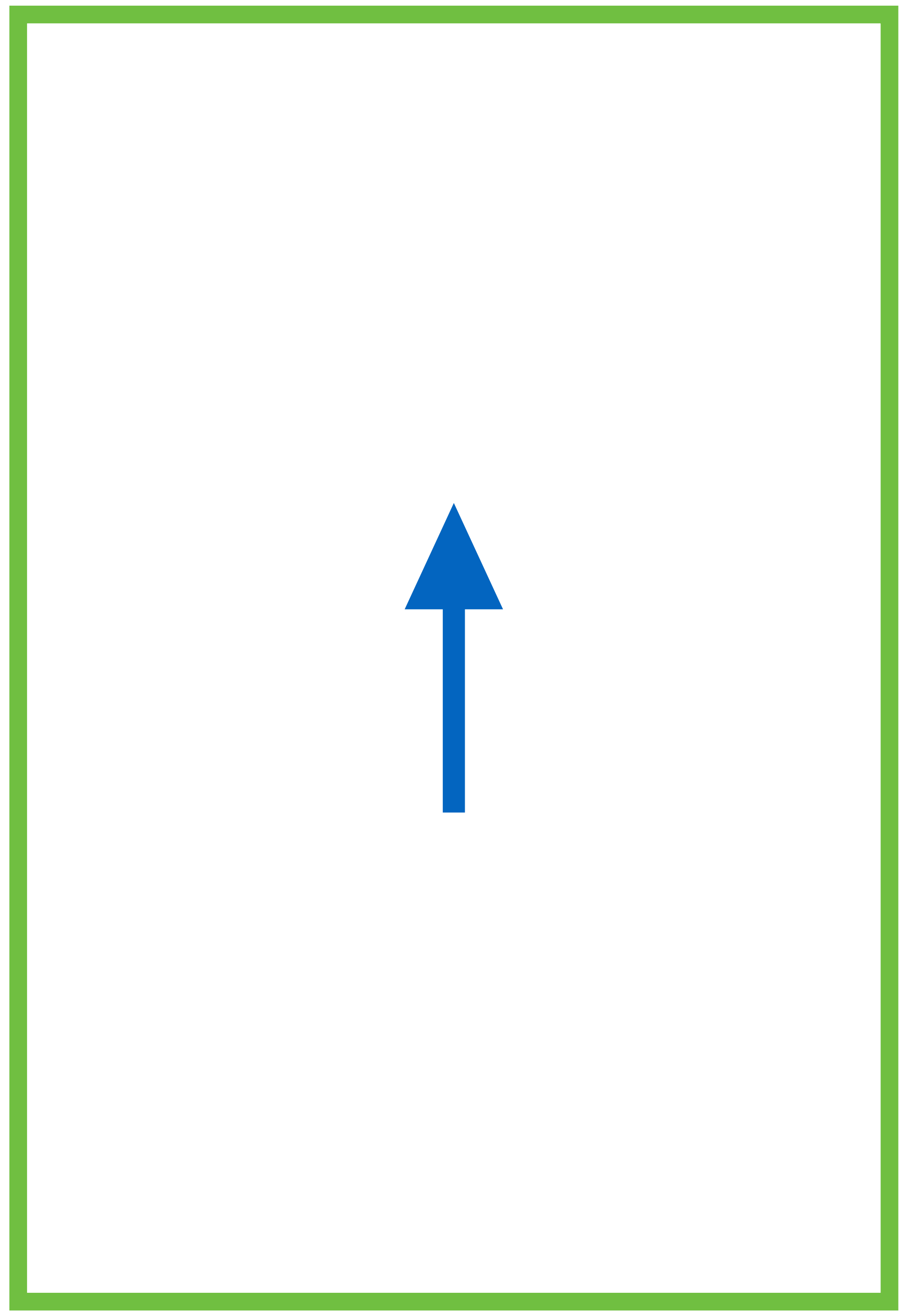
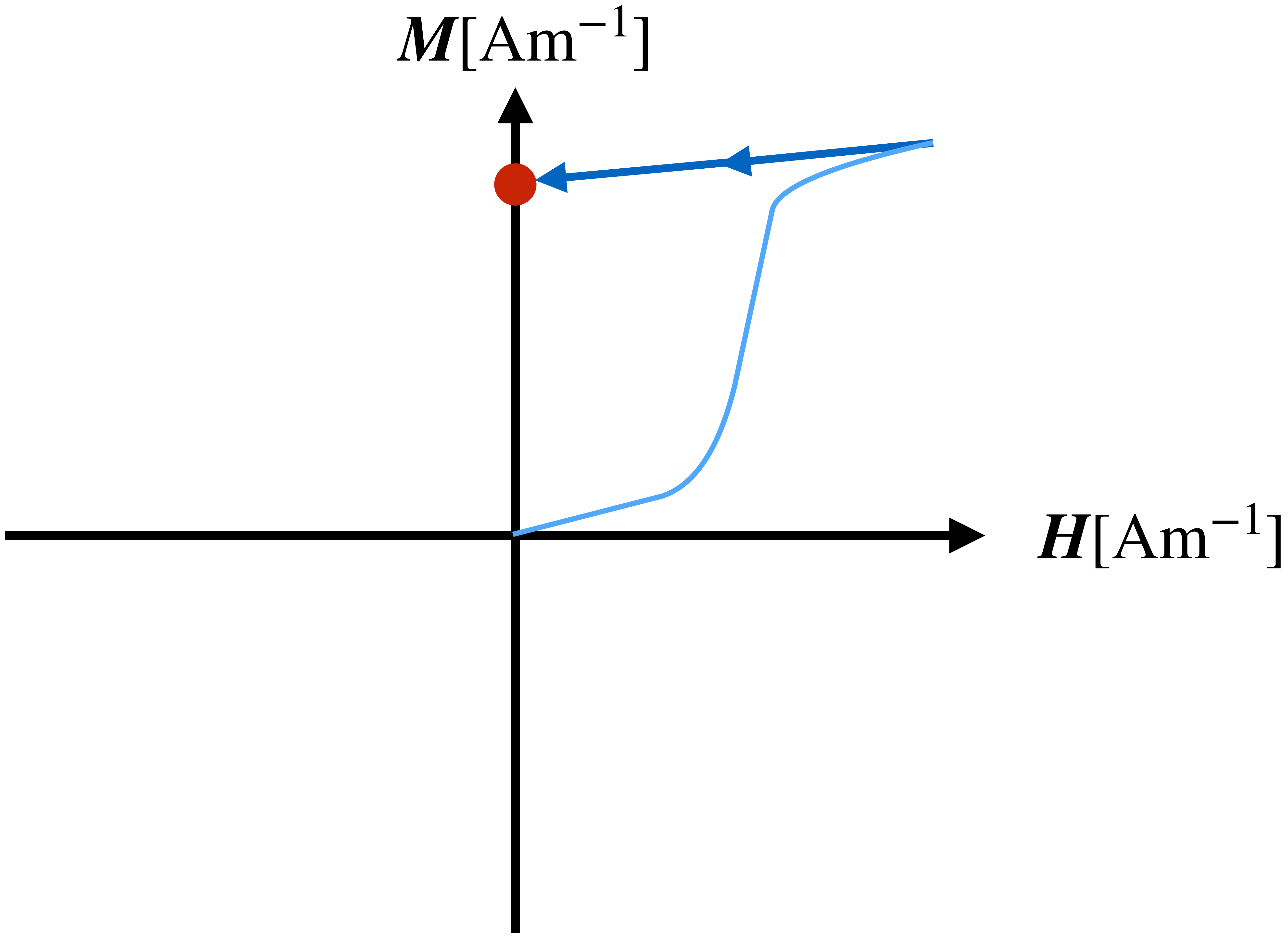


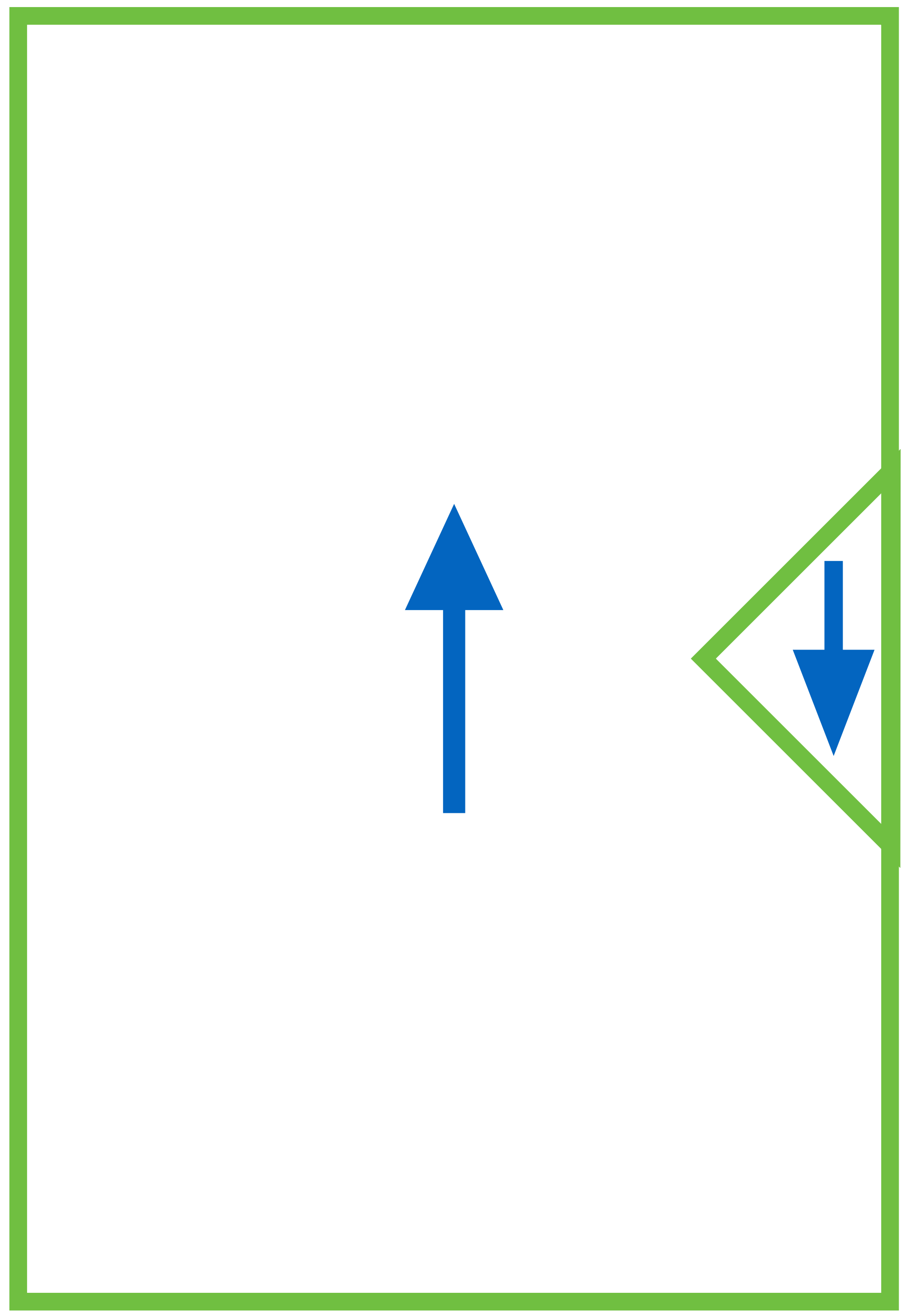


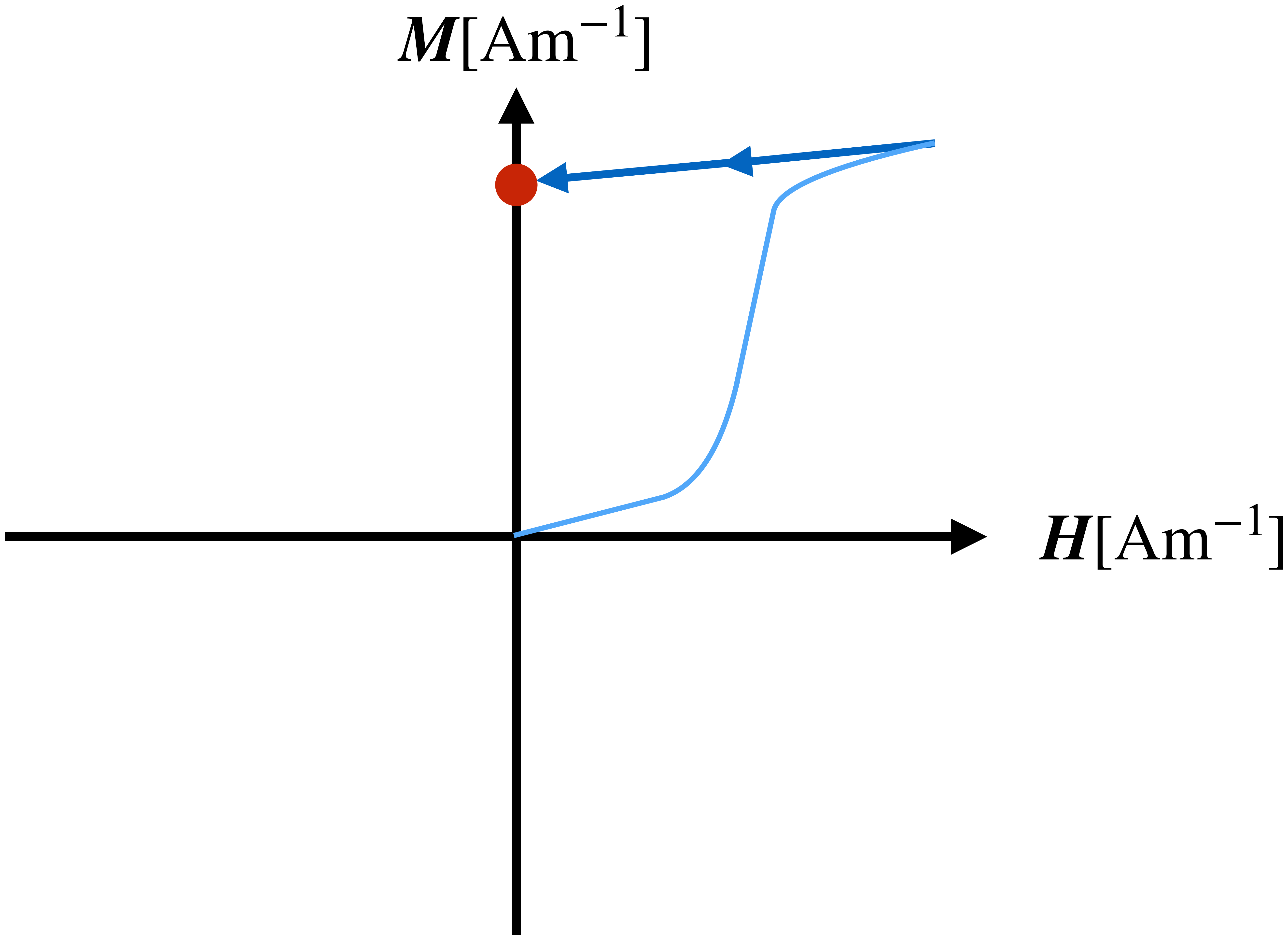
Hysteresis loop



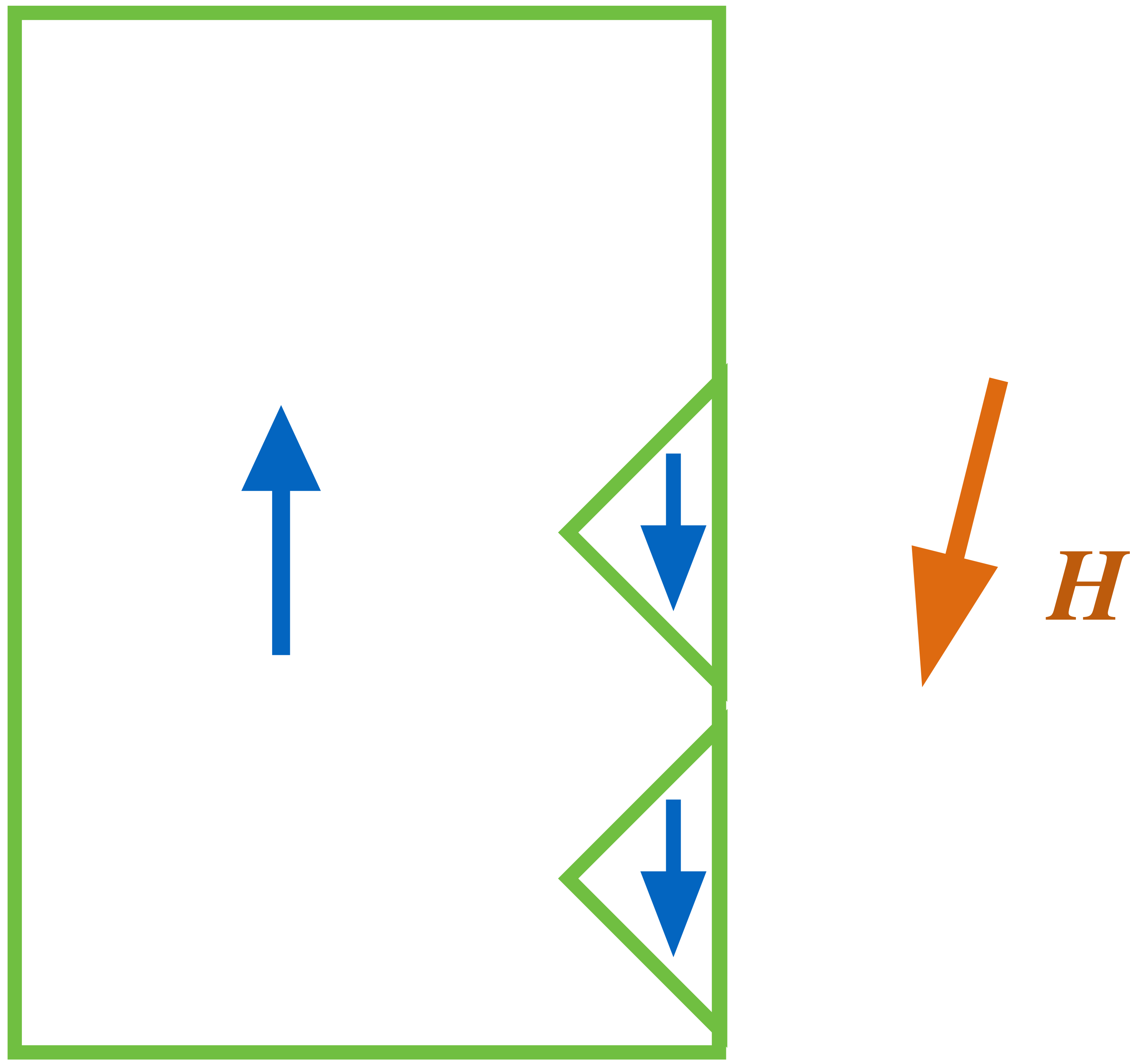


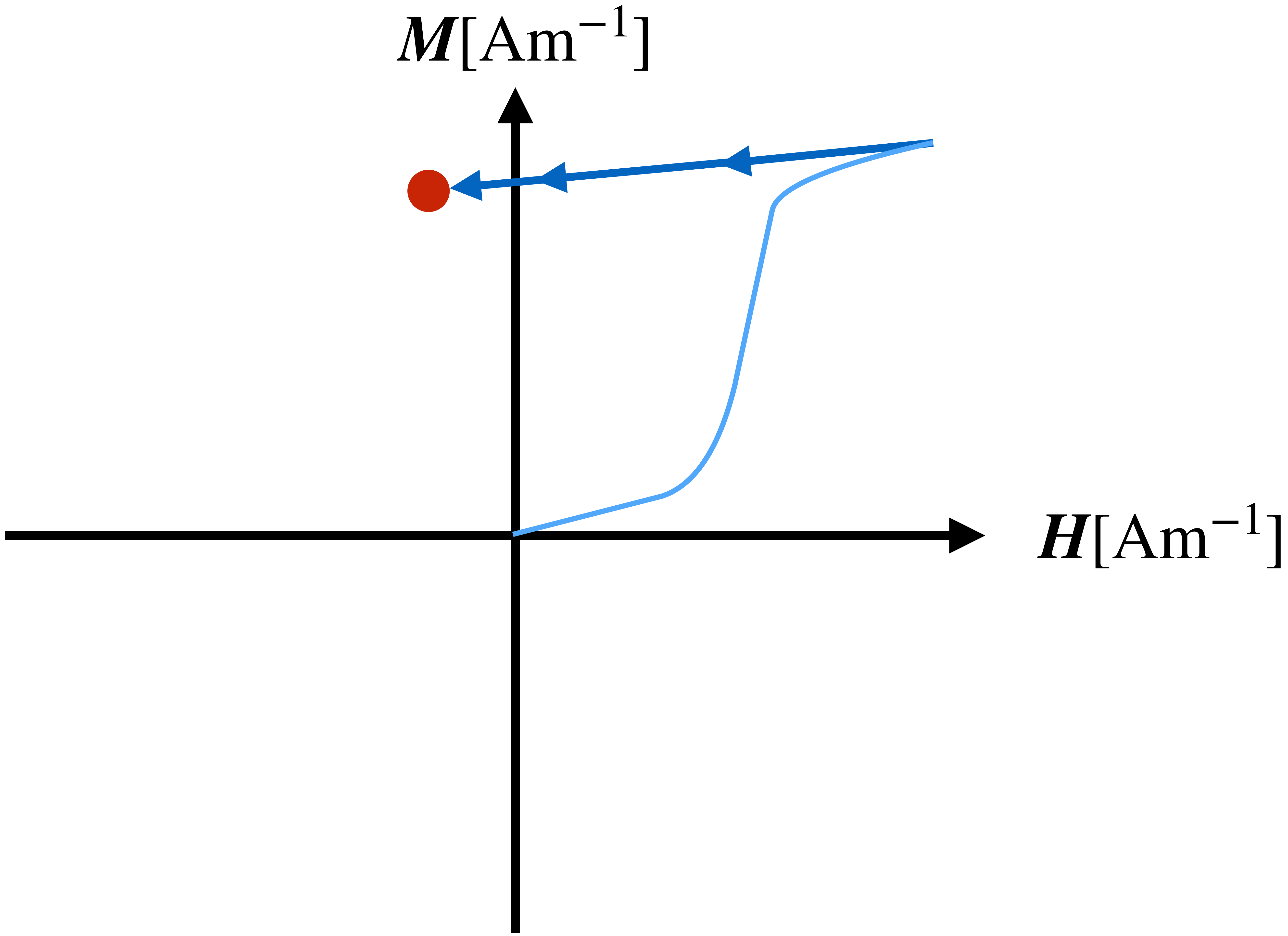
Hysteresis loop



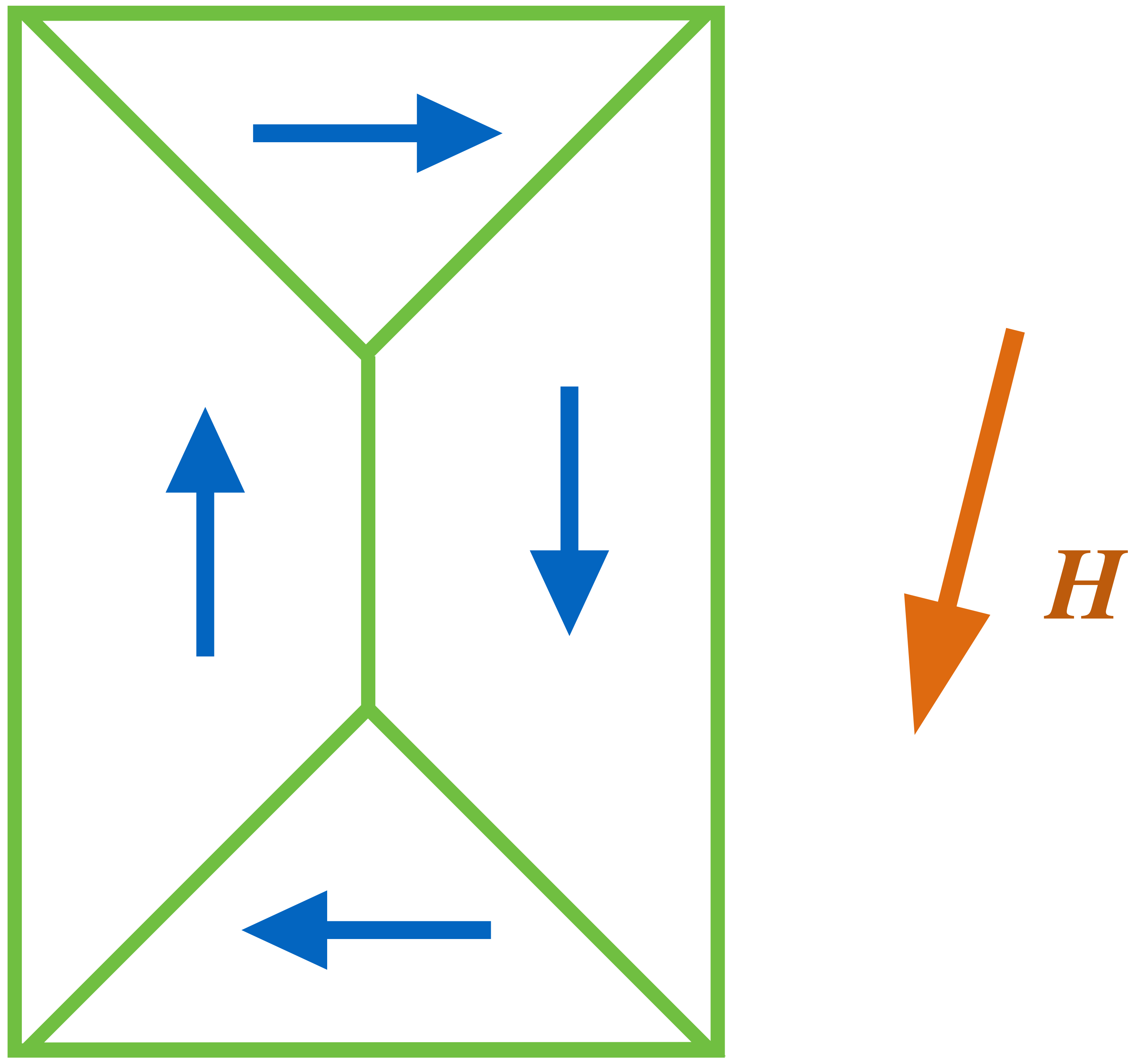


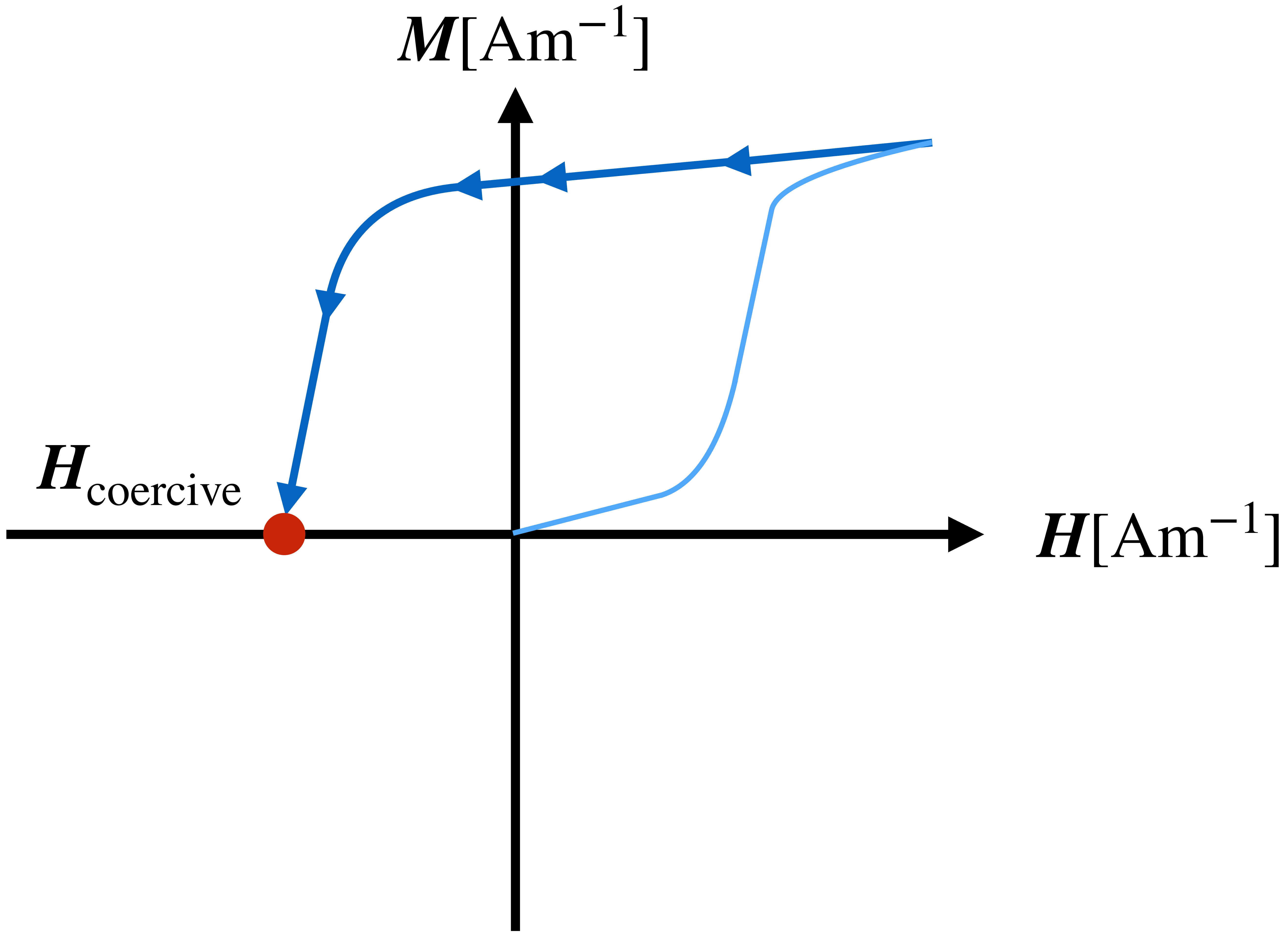
Hysteresis loop



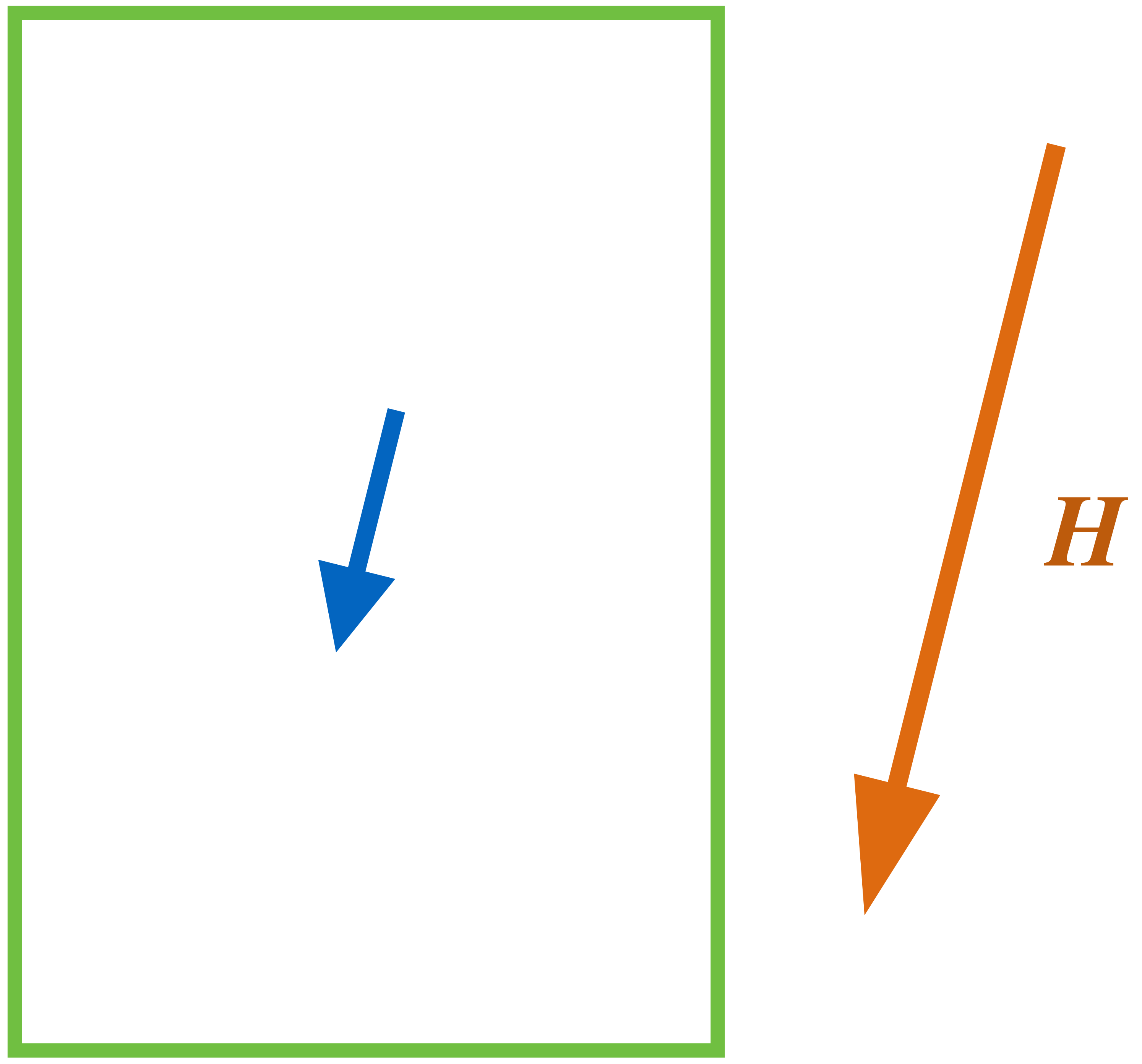


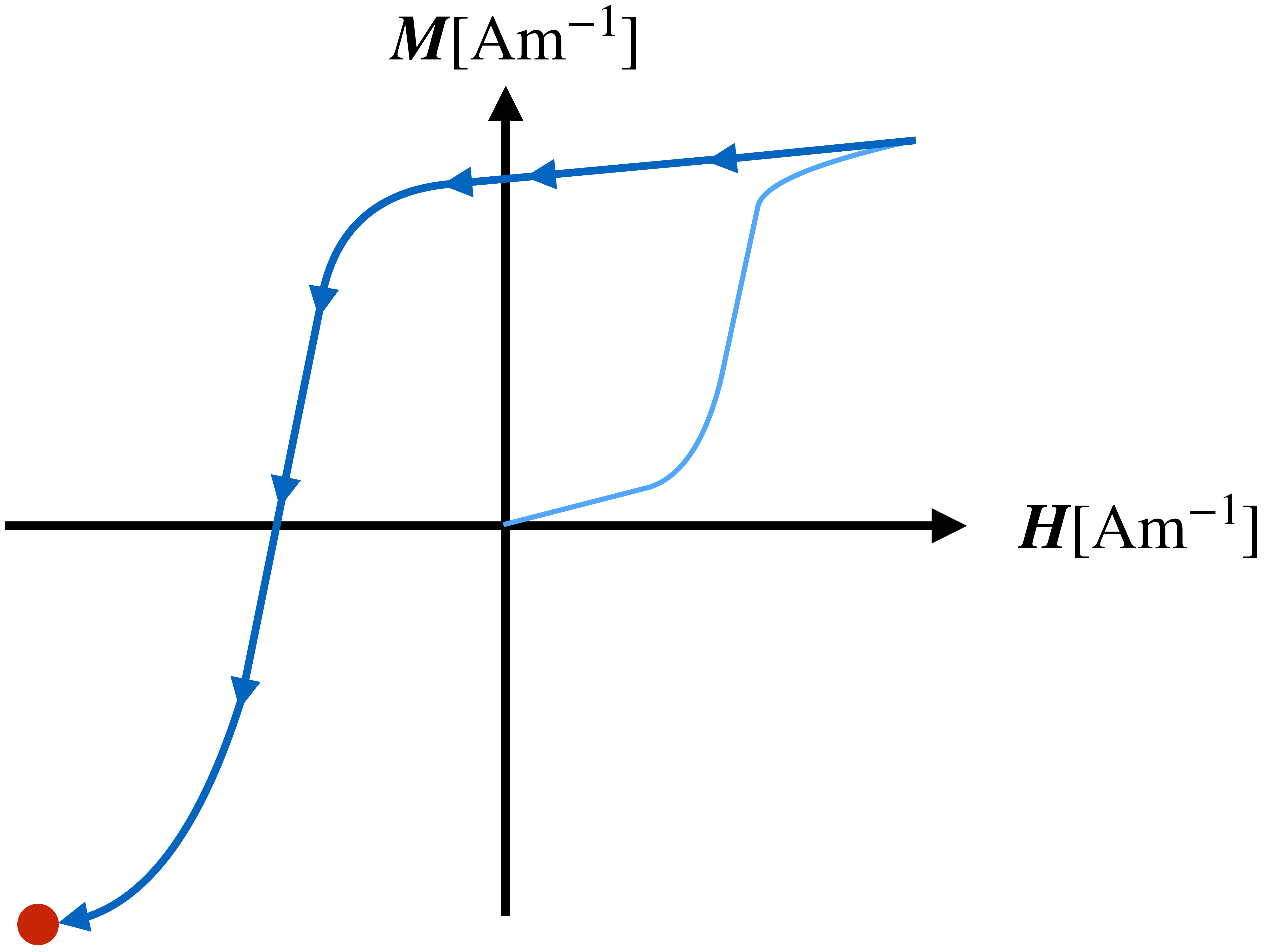
Hysteresis loop



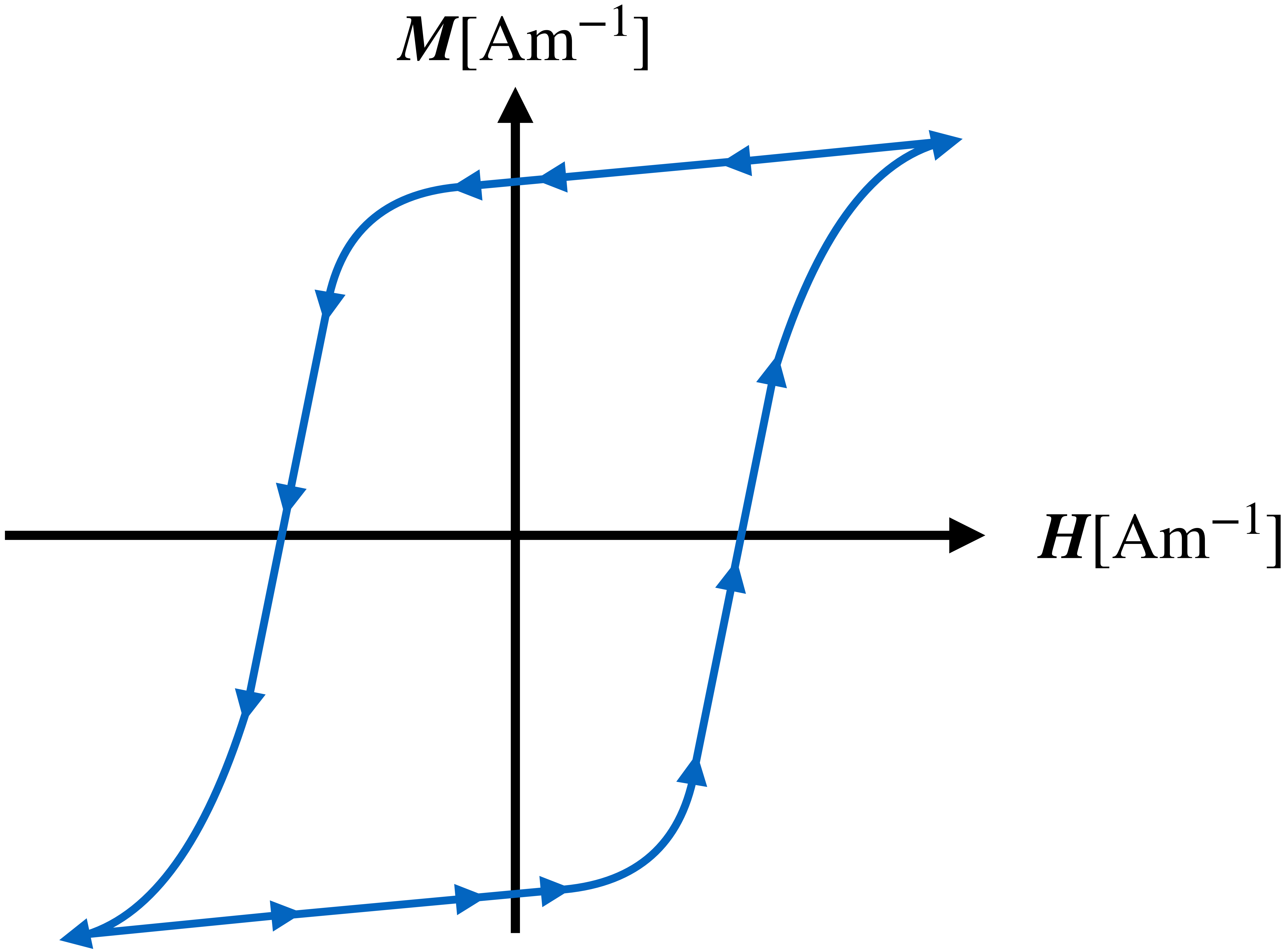


Hysteresis loop

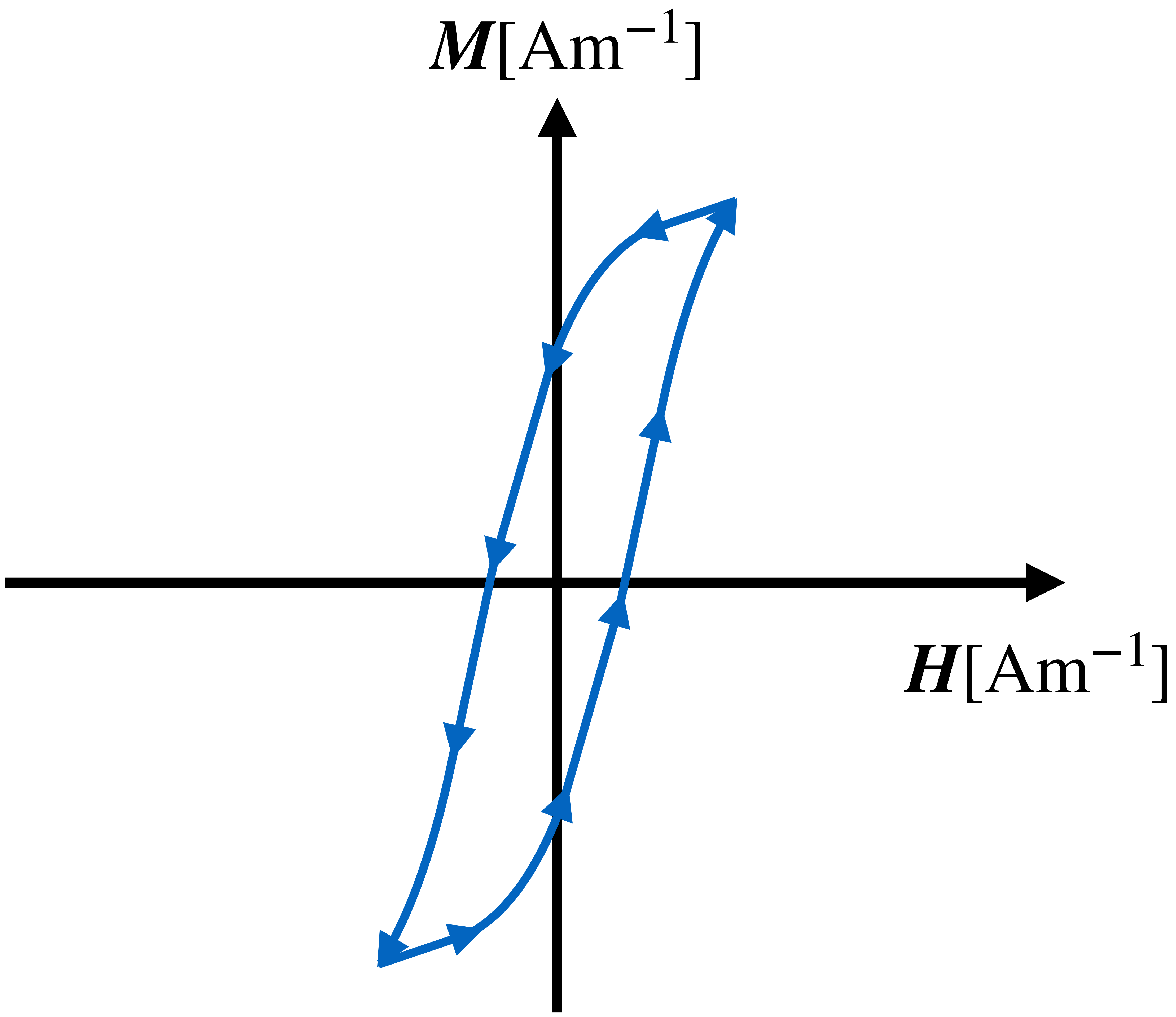




Hysteresis loop

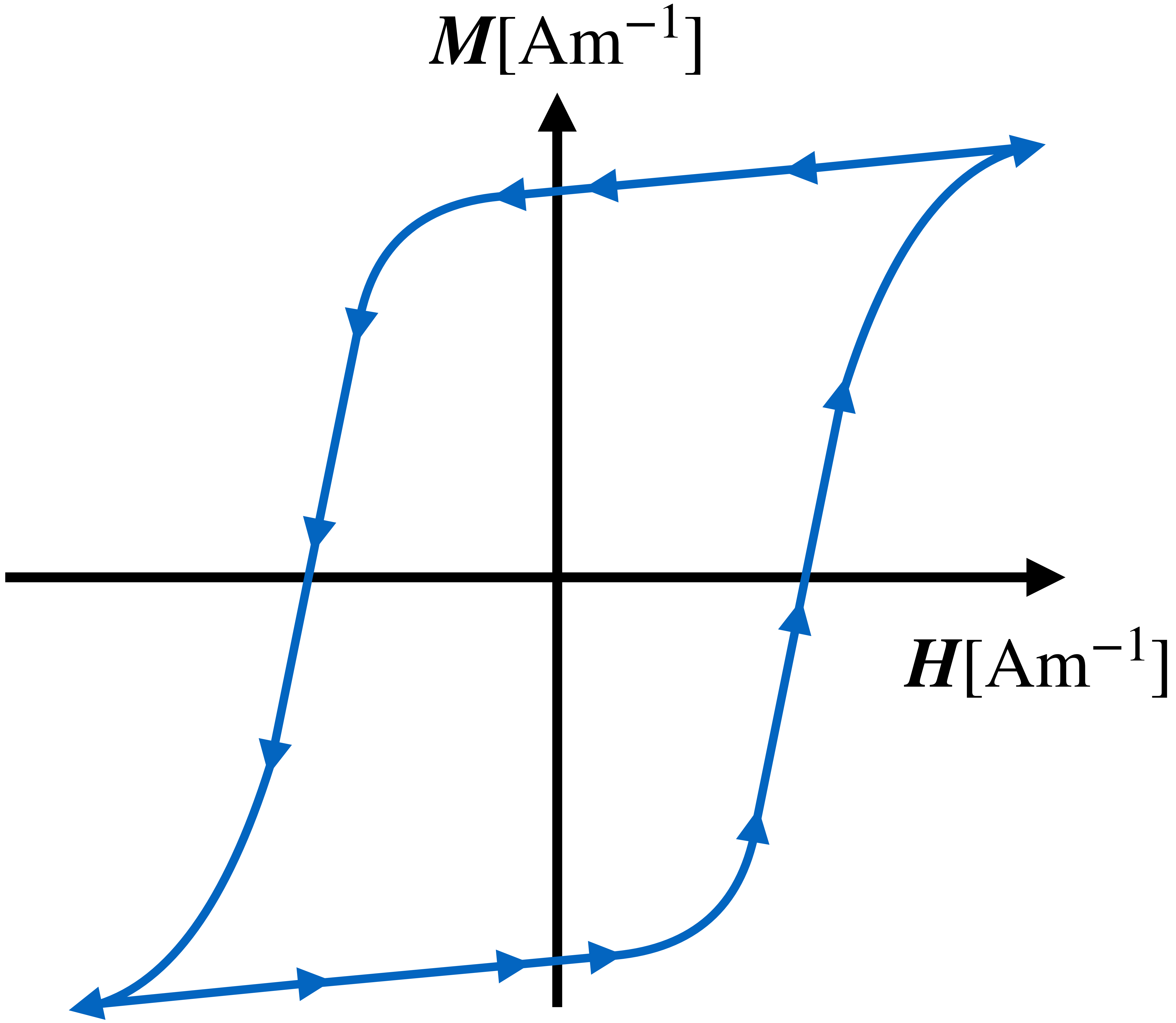


Designing hysteresis loops: soft magnets



- Easily magnetised and demagnetised
- High purity with few defects to pin domain walls
- Used in transformers (need to reverse direction rapidly)

Designing hysteresis loops: hard magnets



- Large coercive field
- High remnant magnetisation
- Add defects to pin domain walls
- Used as permanent magnets (need to have robust magnetisation)