UNIVERSITY OF CAMBRIDGE

Electric polarisation in materials

Lecture 4

Bartomeu Monserrat

Course B: Materials for Devices

Professor M does Science

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

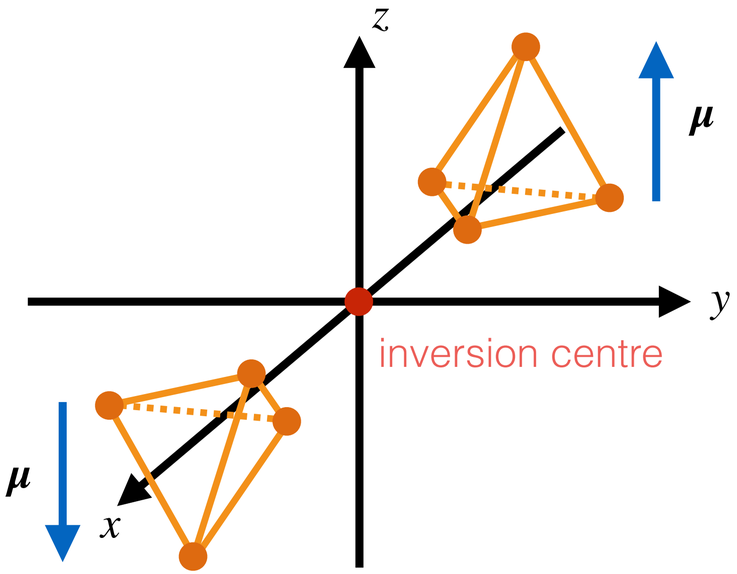
centrosymmetric crystal

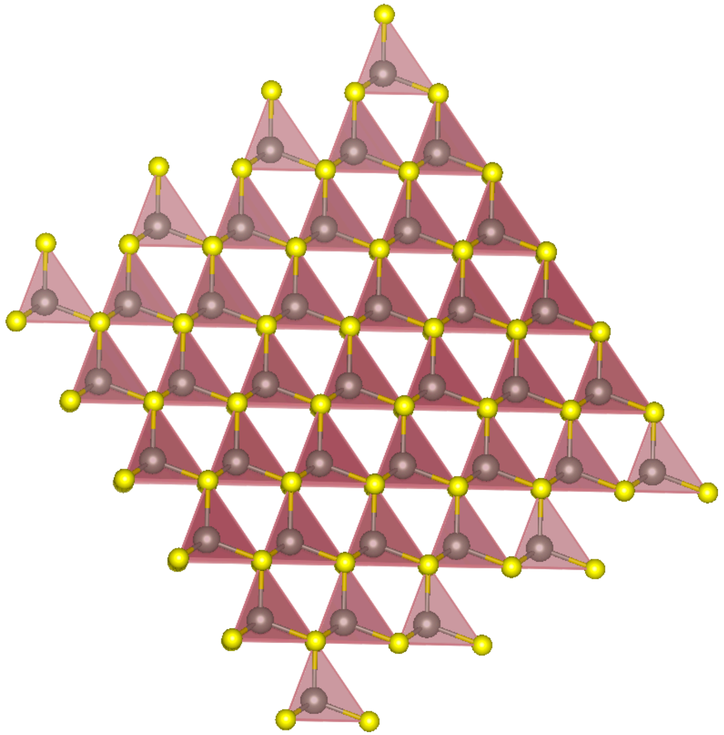
noncentrosymmetric crystal

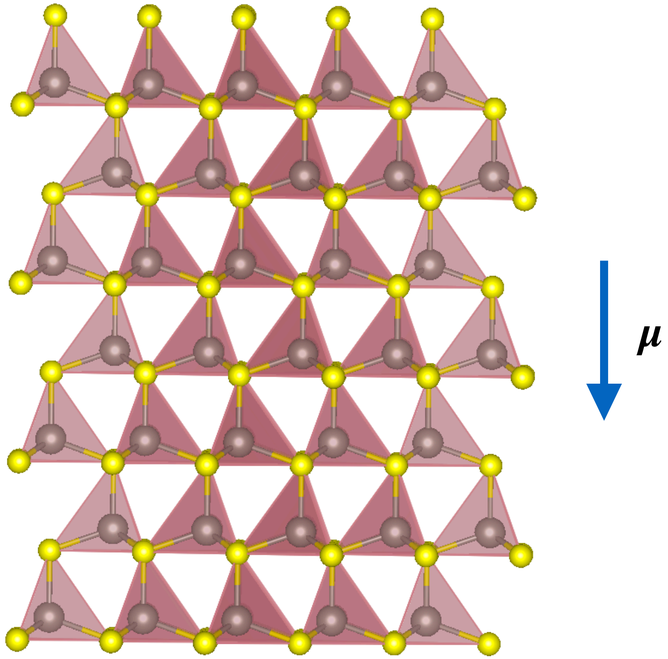
non-polar

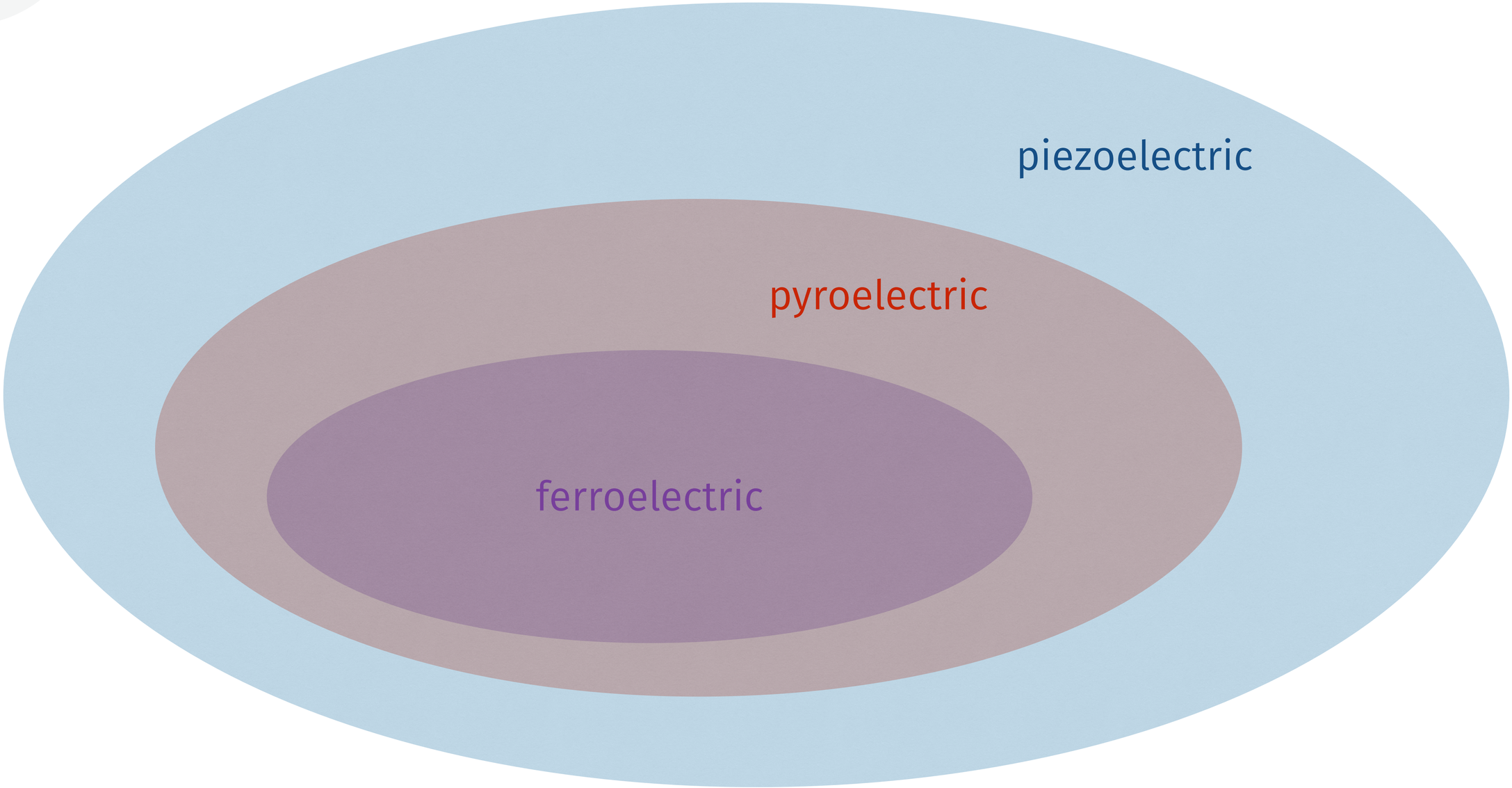
non-polar

polar



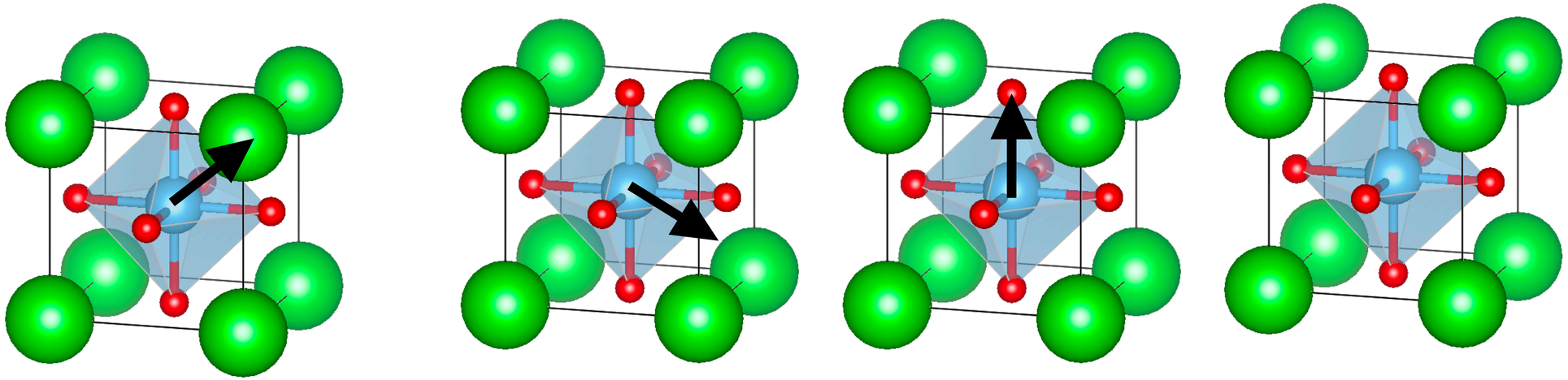




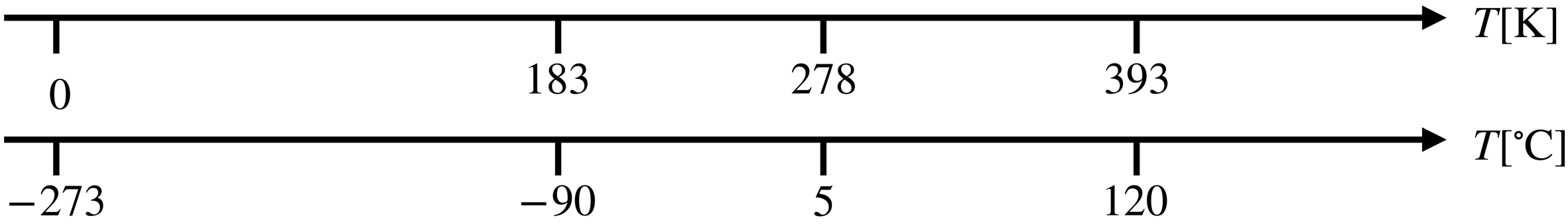

piezoelectric
pyroelectric
ferroelectric

Phase diagram of $BaTiO_3$

rhombohedral	orthorhombic	tetragonal	cubic
$a = b = c$	$a \neq b \neq c$	$a = b \neq c$	$a = b = c$
$\alpha = \beta = \gamma \neq 90^\circ$	$\alpha = \beta = \gamma = 90^\circ$	$\alpha = \beta = \gamma = 90^\circ$	$\alpha = \beta = \gamma = 90^\circ$

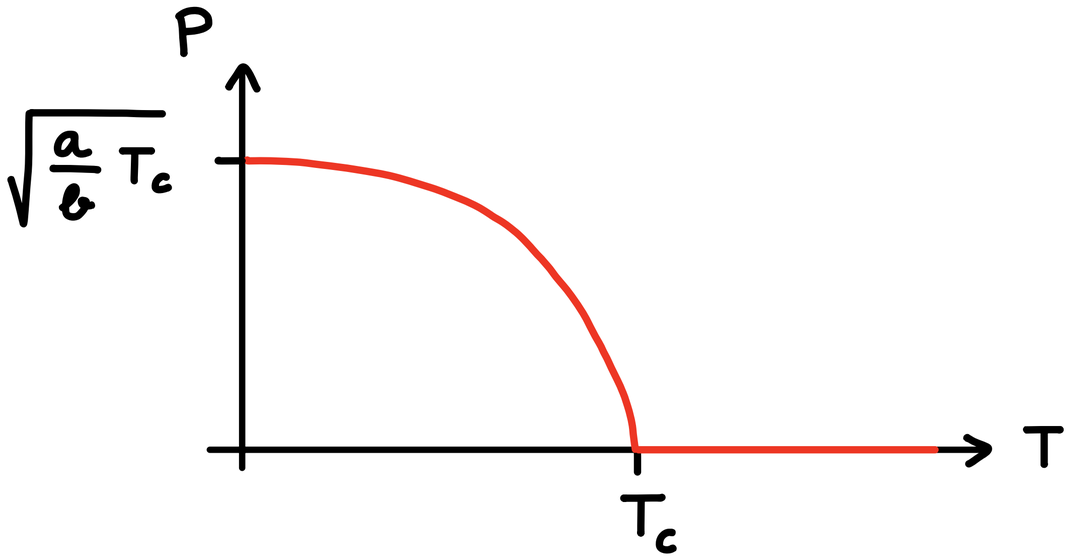


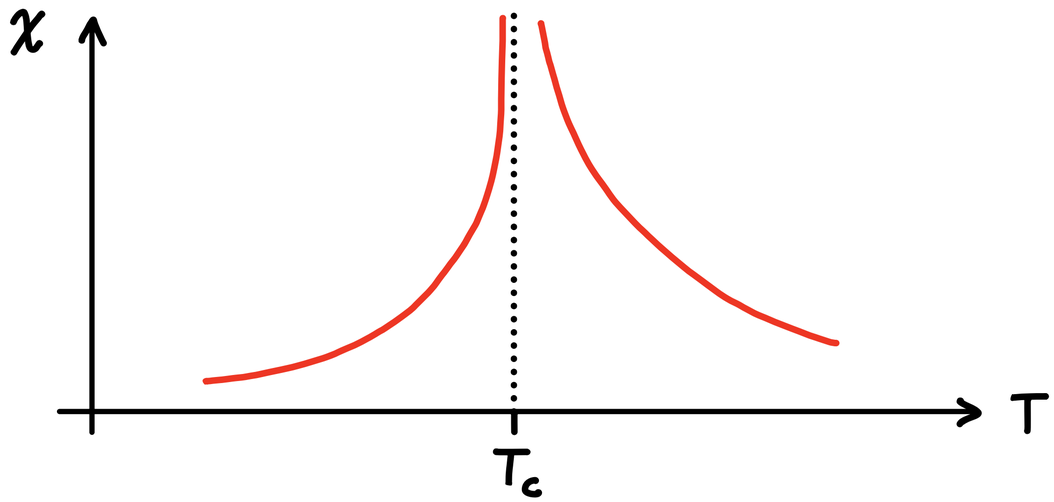
$\langle 111 \rangle$ distortion | $\langle 110 \rangle$ distortion | $\langle 100 \rangle$ distortion



Landau theory

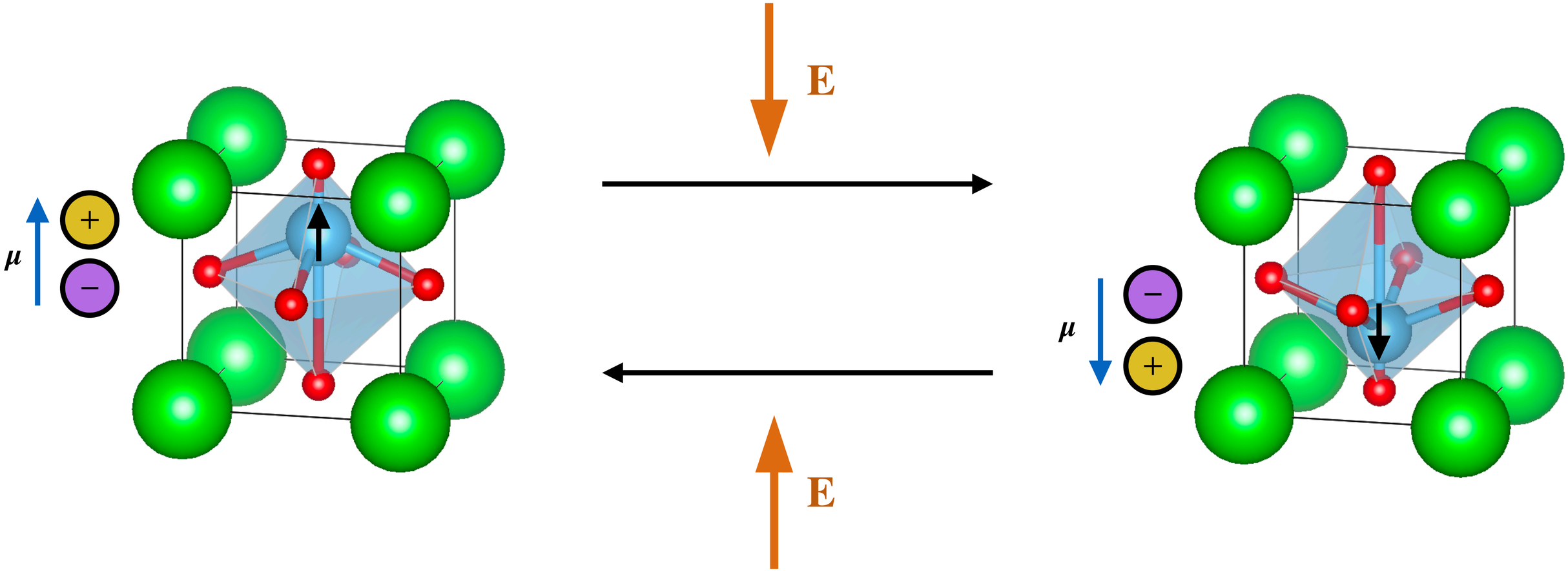
$$\mathcal{F}(P,T) = a(T - T_c)P^2 + bP^4 - EP$$





Ferroelectricity

- Ferroelectricity: spontaneous polarisation that can be reversed by electric field

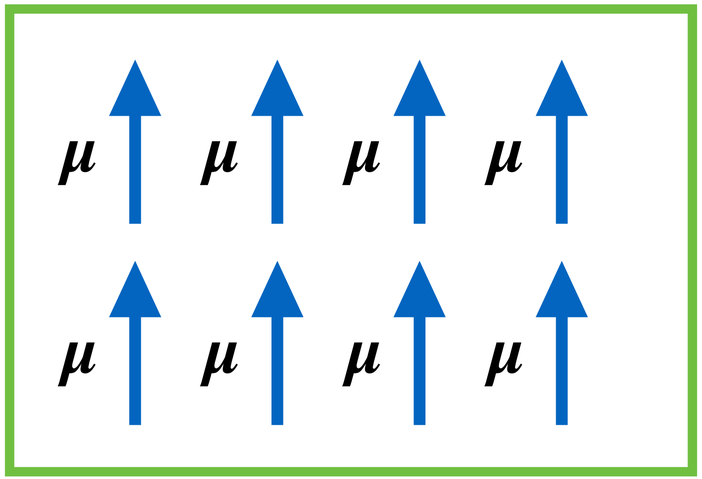


Dipole-dipole interaction

$$U_{\uparrow\uparrow} < U_{\uparrow\downarrow}$$

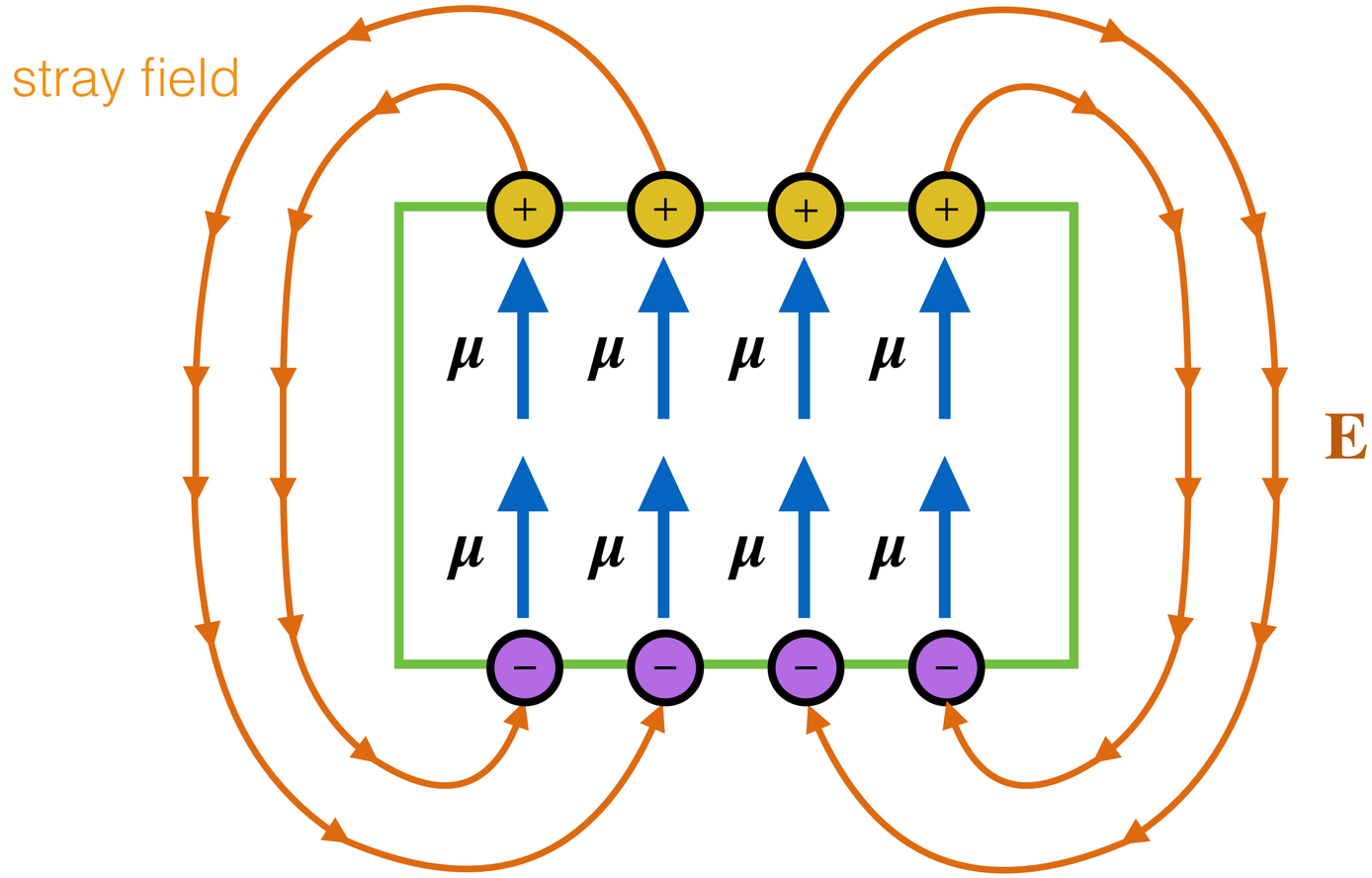
Polarisation domain

- Domain: region in a material in which the polarisation is in the same direction



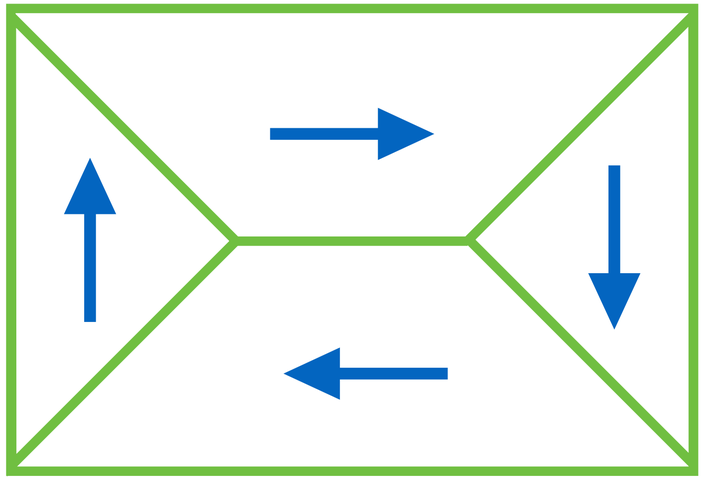
Stray field

- Domain: region in a material in which the polarisation is in the same direction

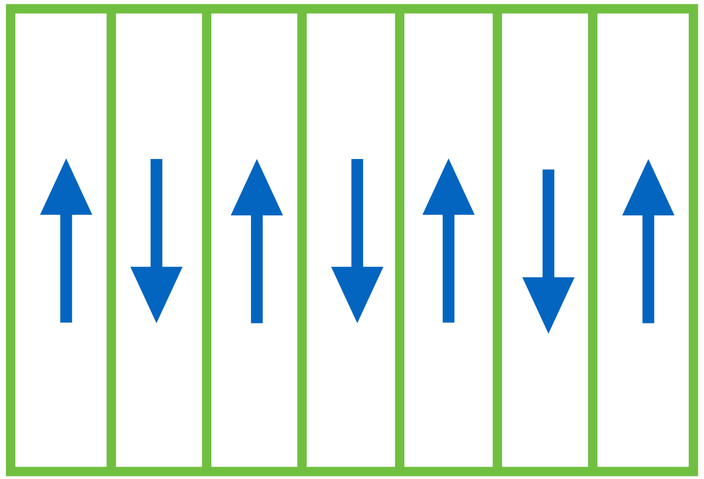


$$u_{\mathbf{E}} = \frac{1}{2}\varepsilon\,|\mathbf{E}|^2$$

Multiple domains

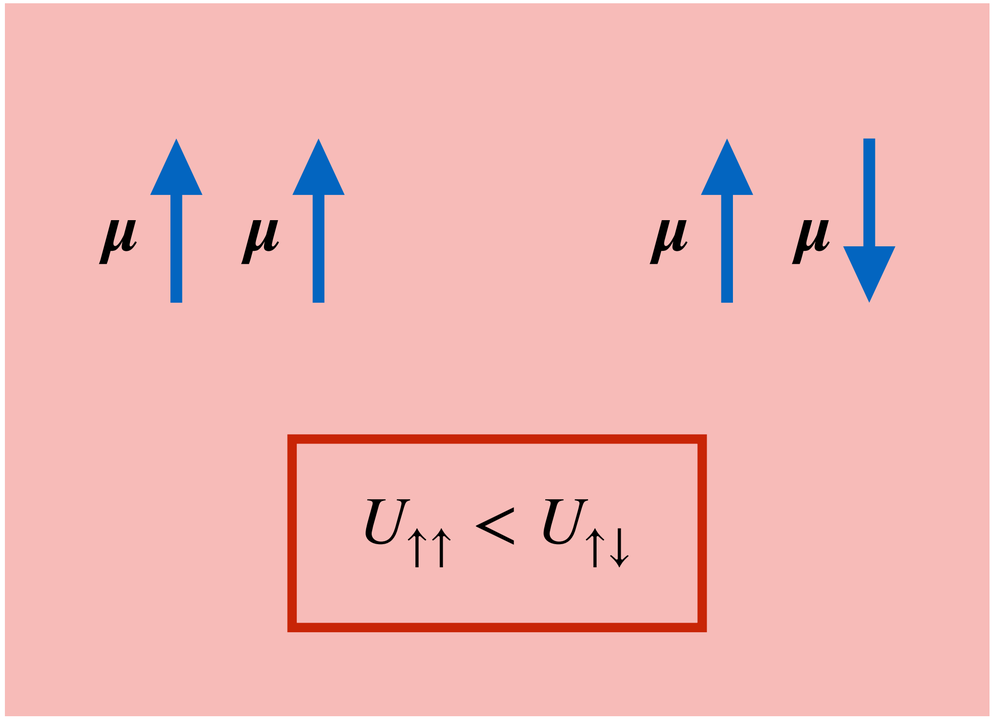


90° domain wall

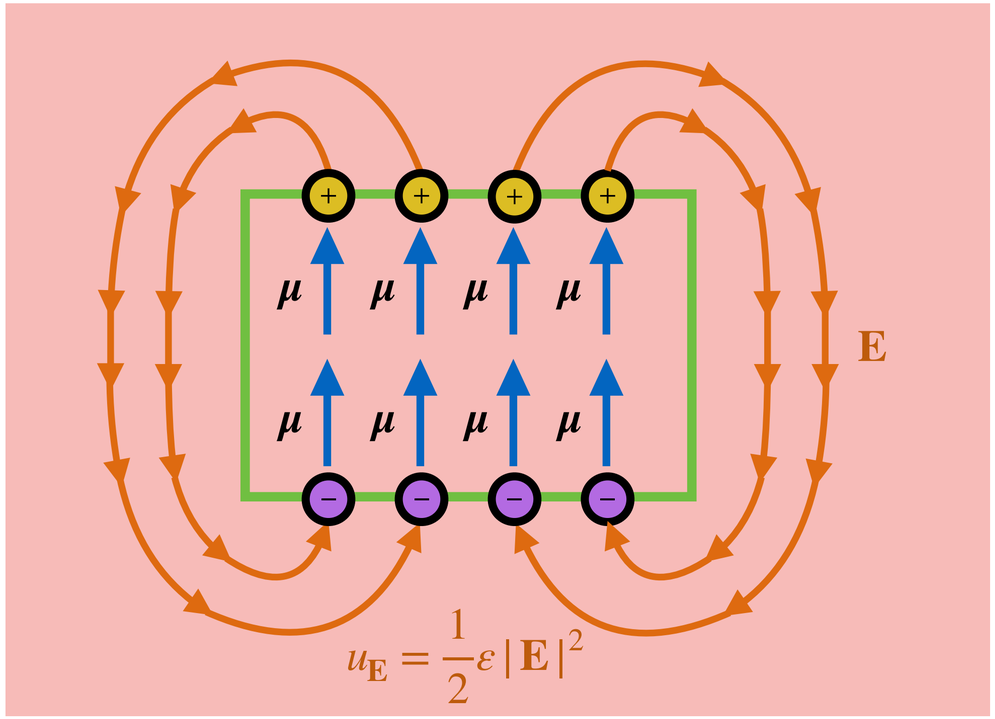


180° domain wall

Energy balance

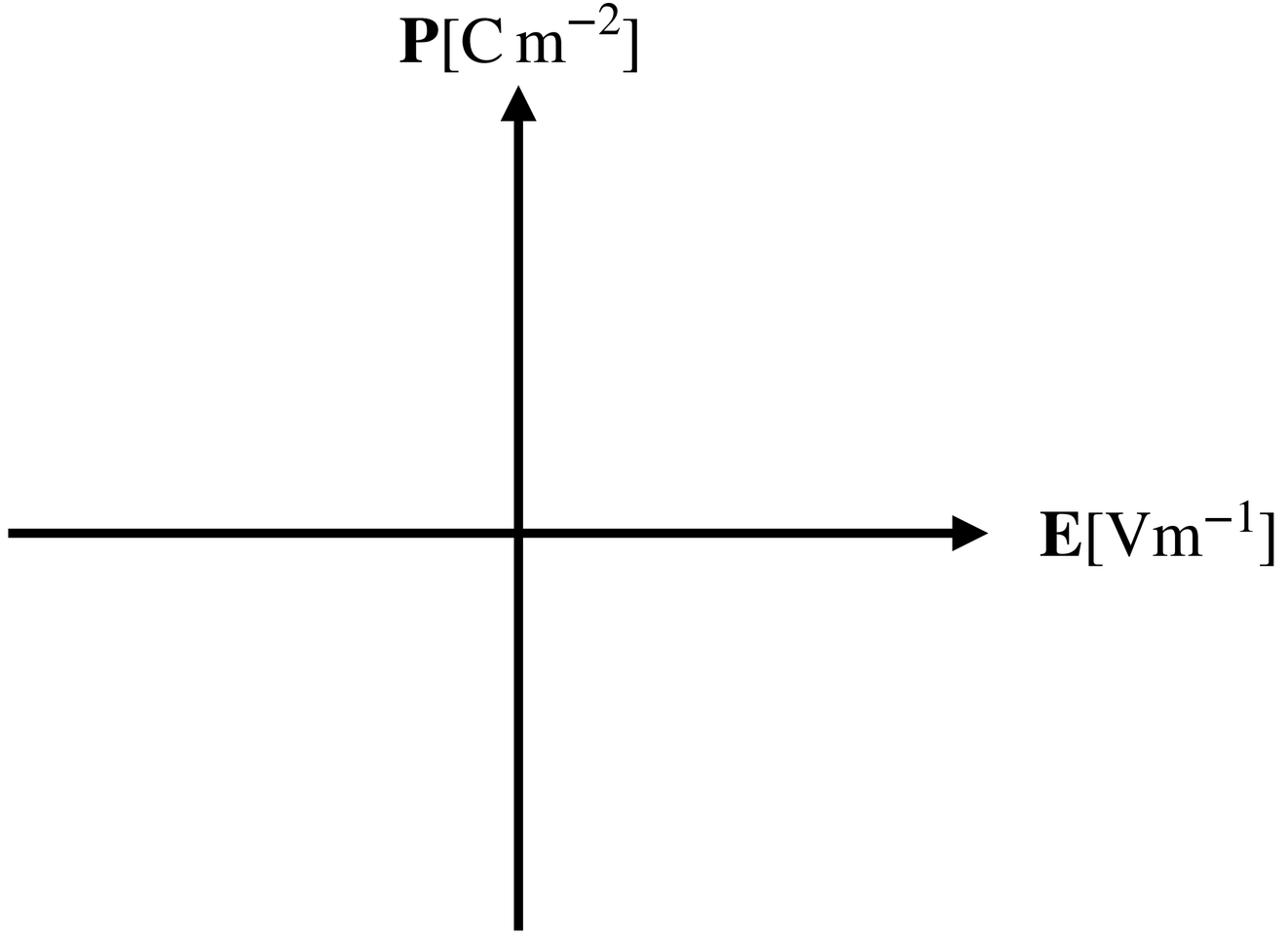


vs.



domain wall energy vs. stray field energy

Hysteresis in a “real” ferroelectric



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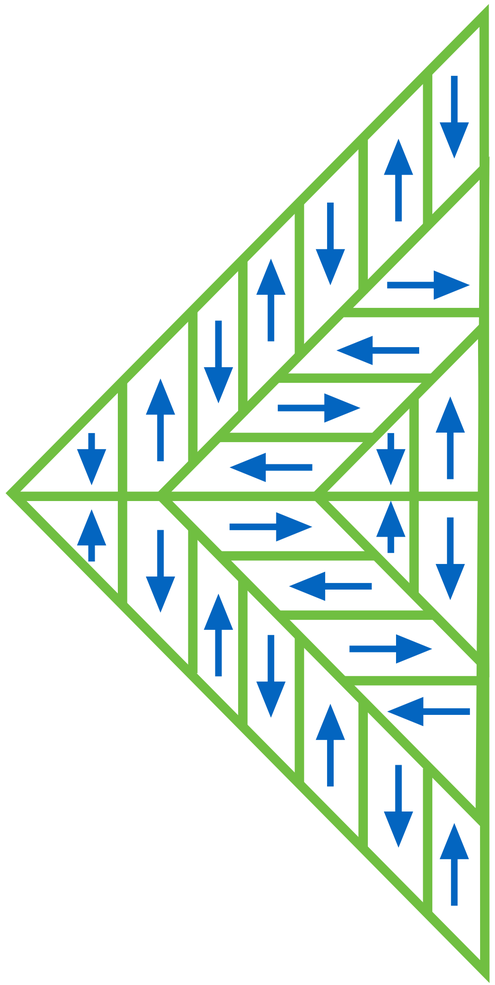
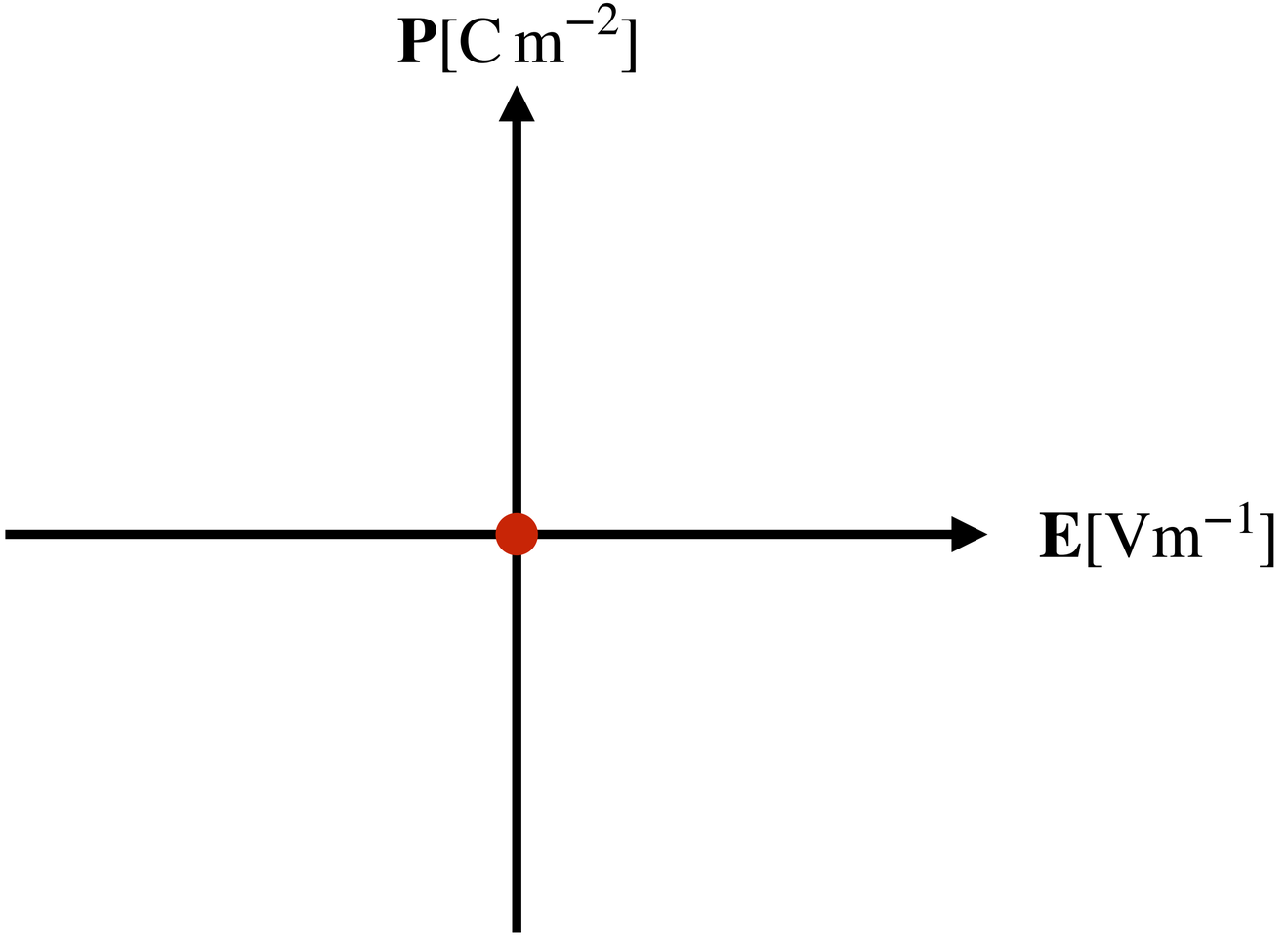
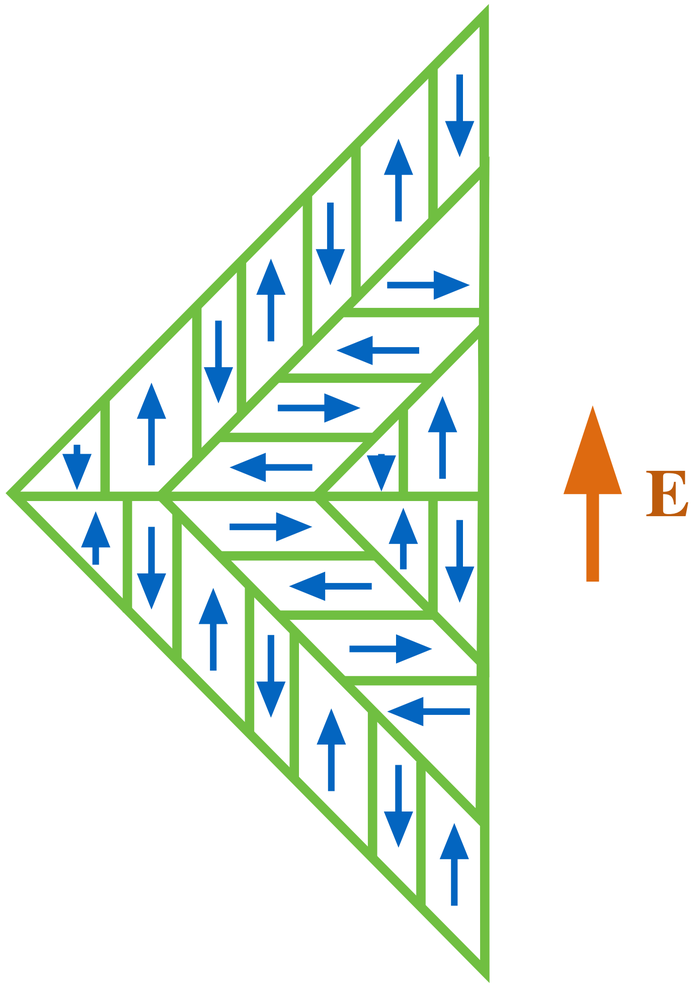
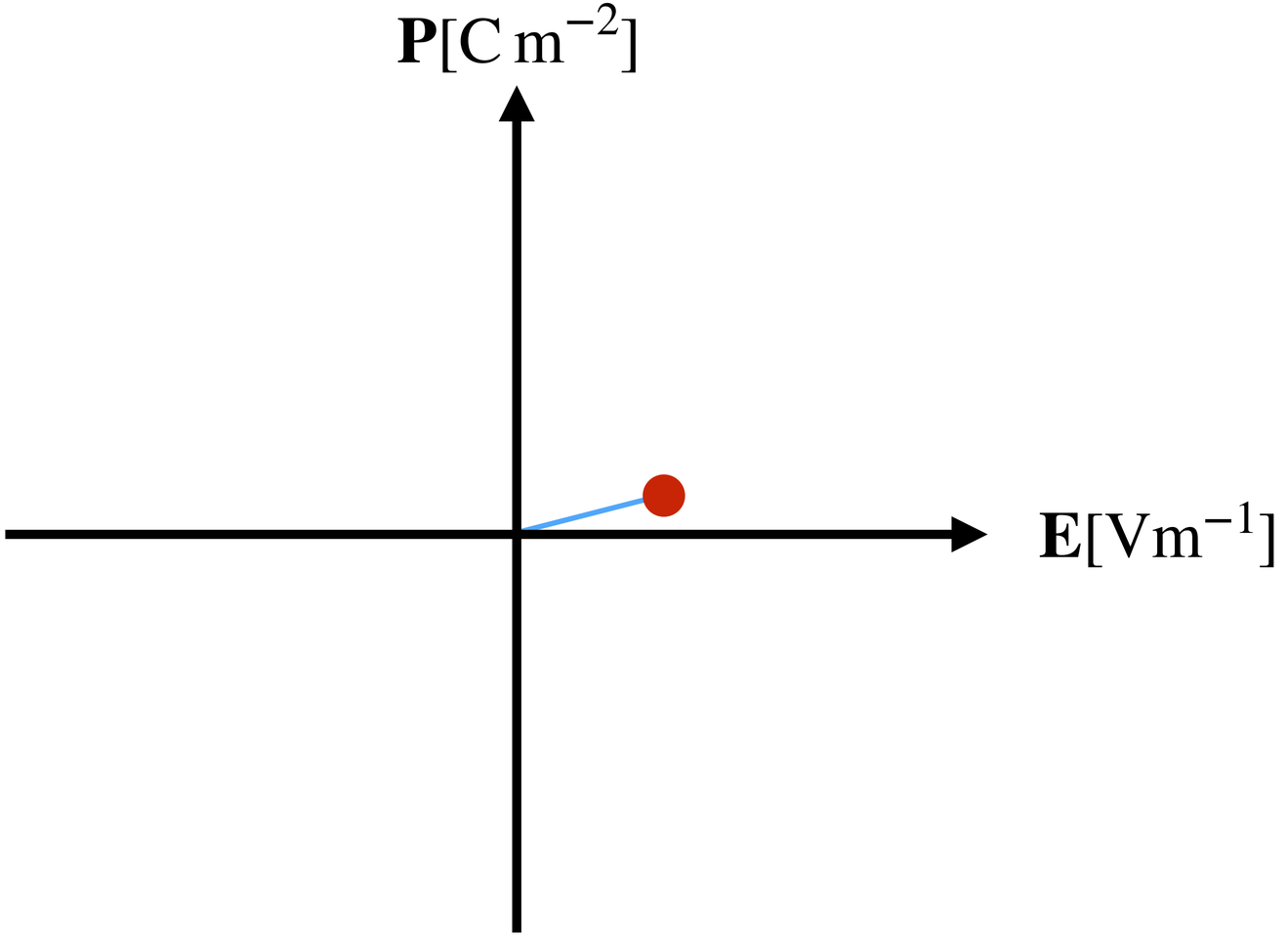


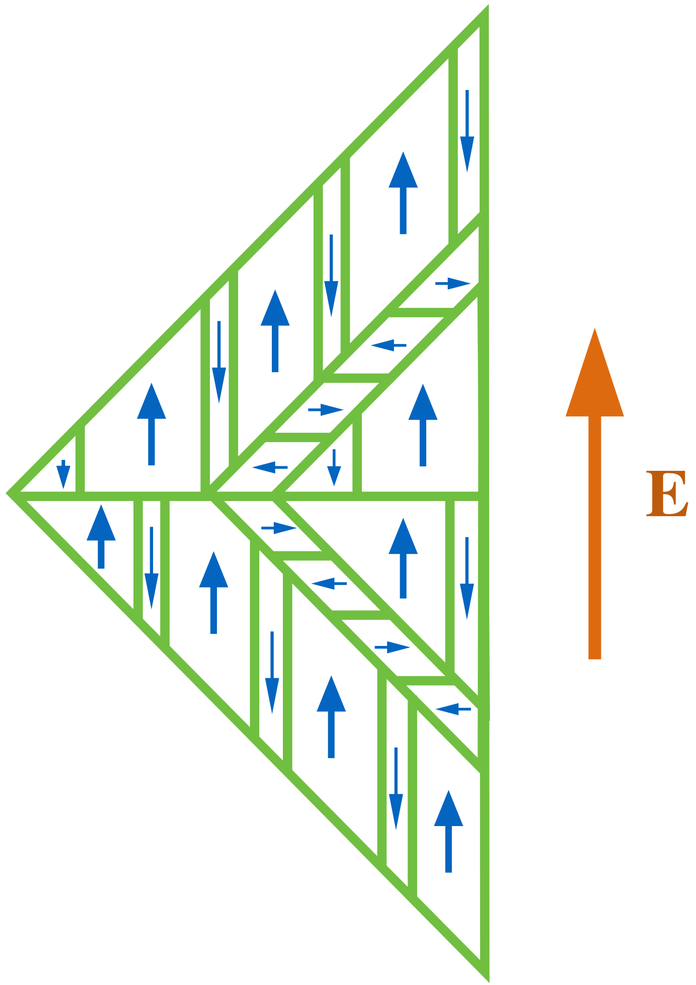


Hysteresis in a “real” ferroelectric





Hysteresis in a “real” ferroelectric



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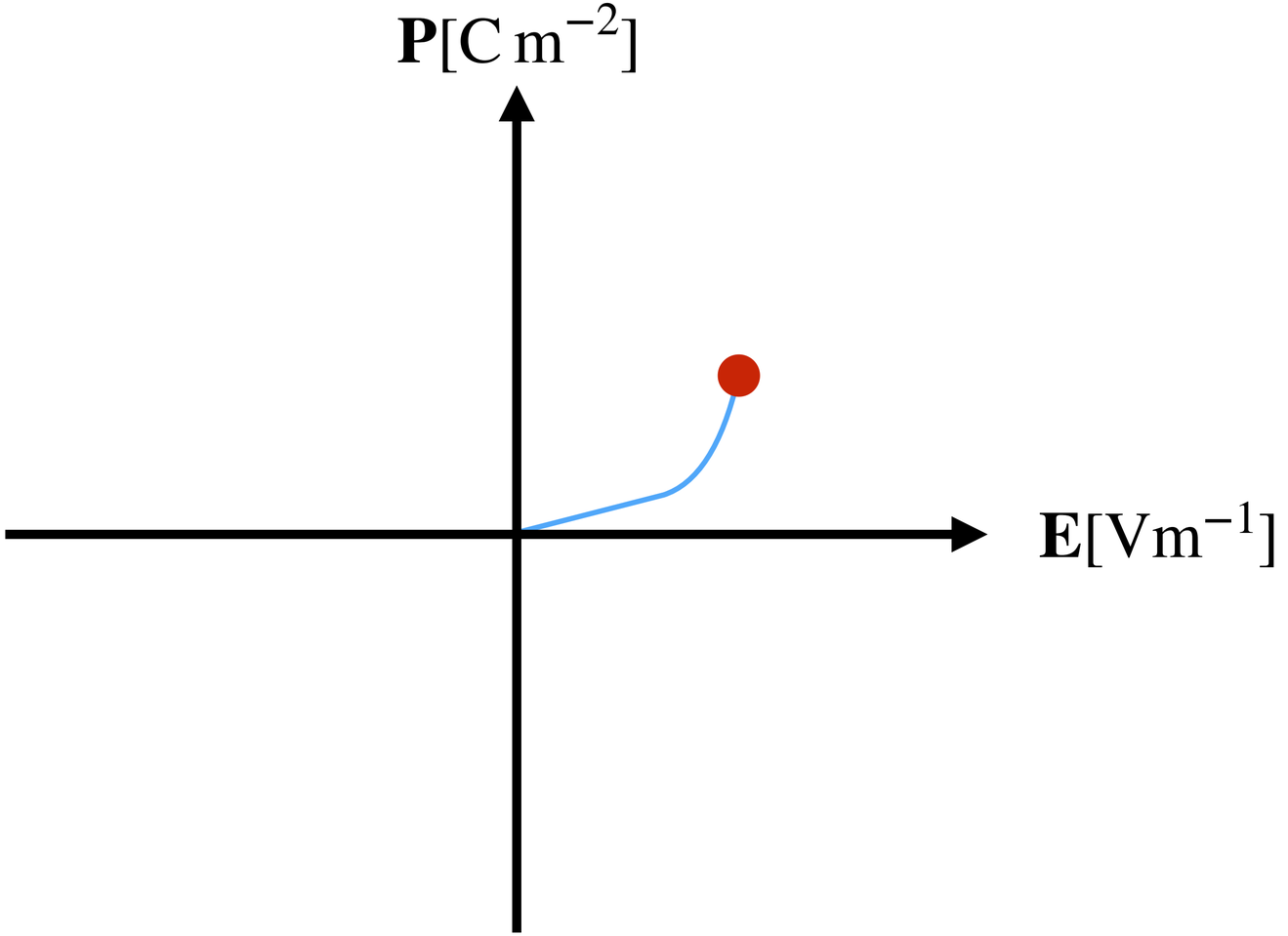
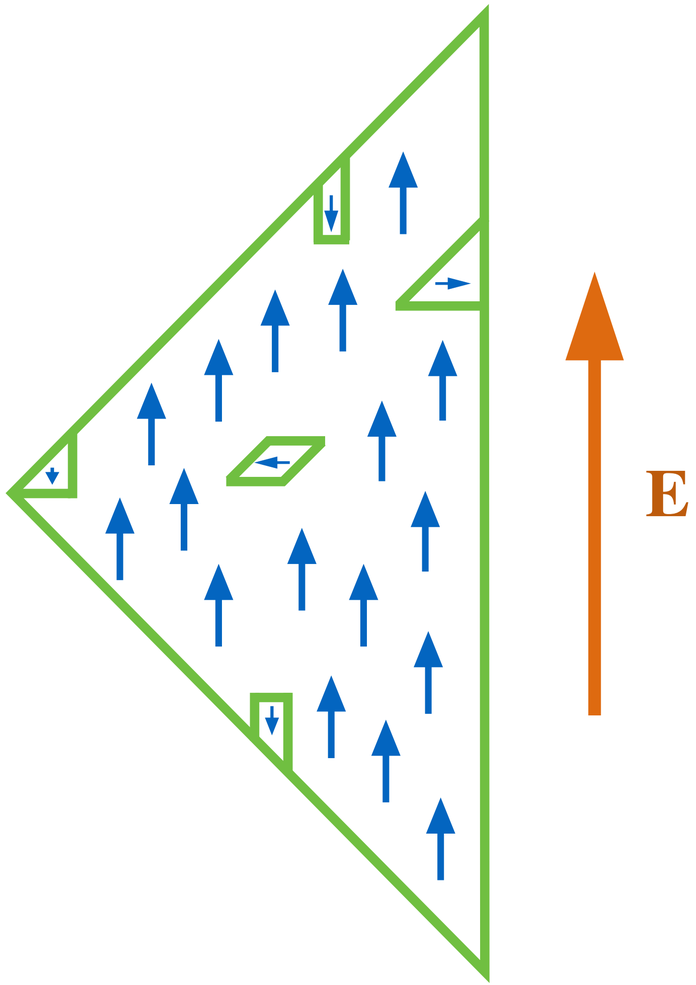
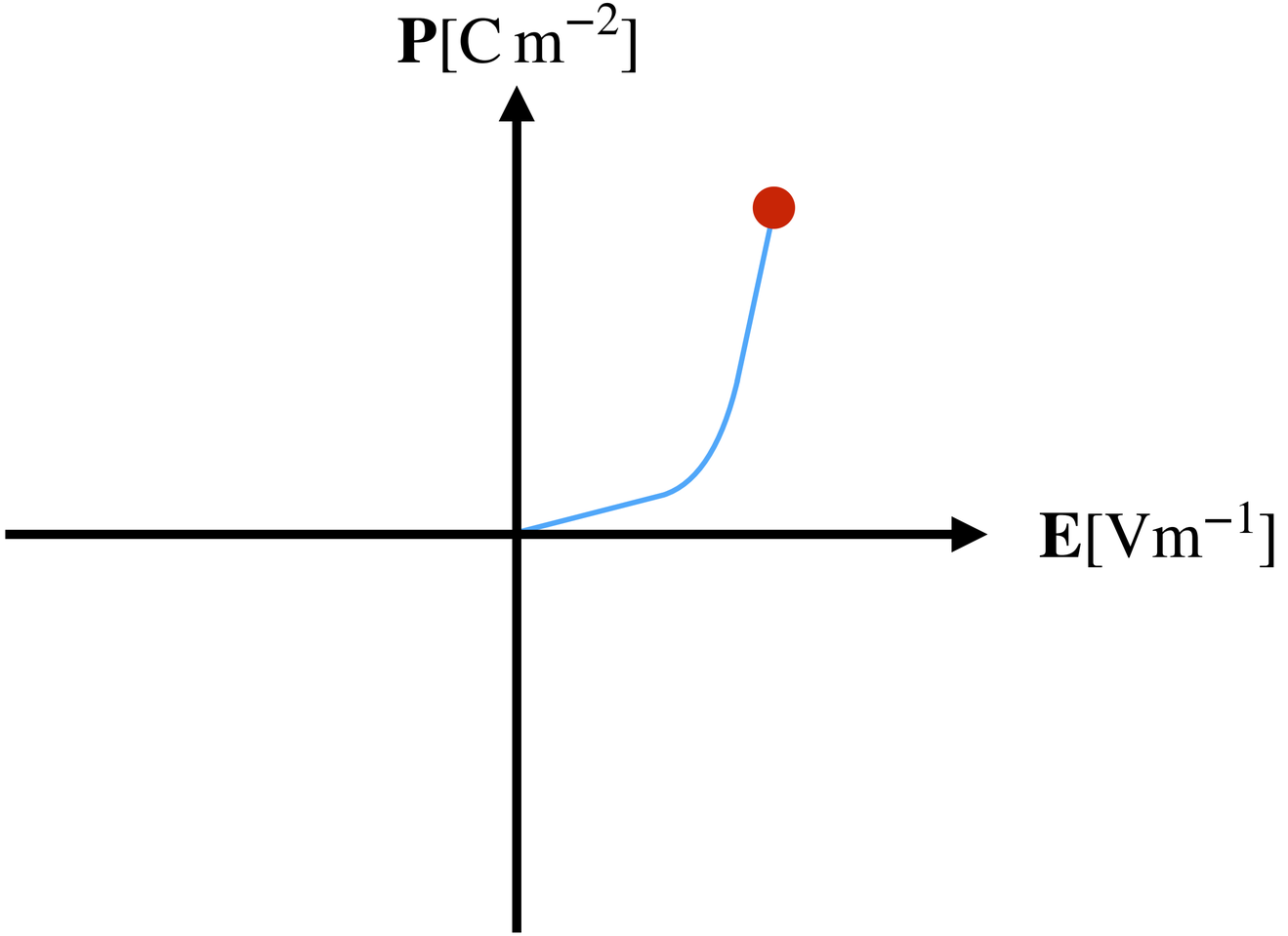
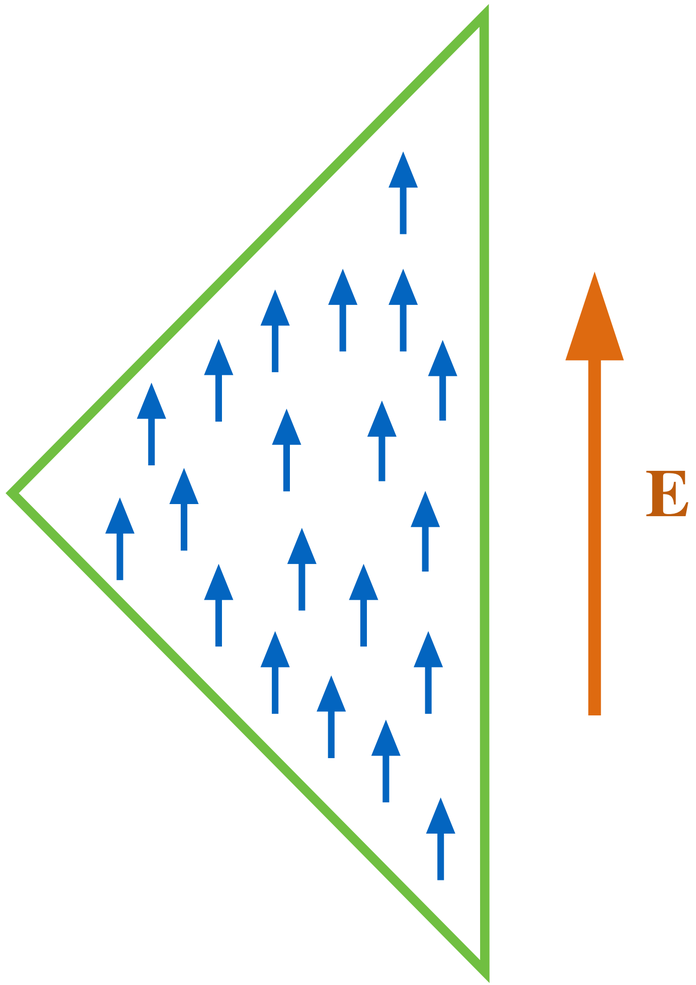


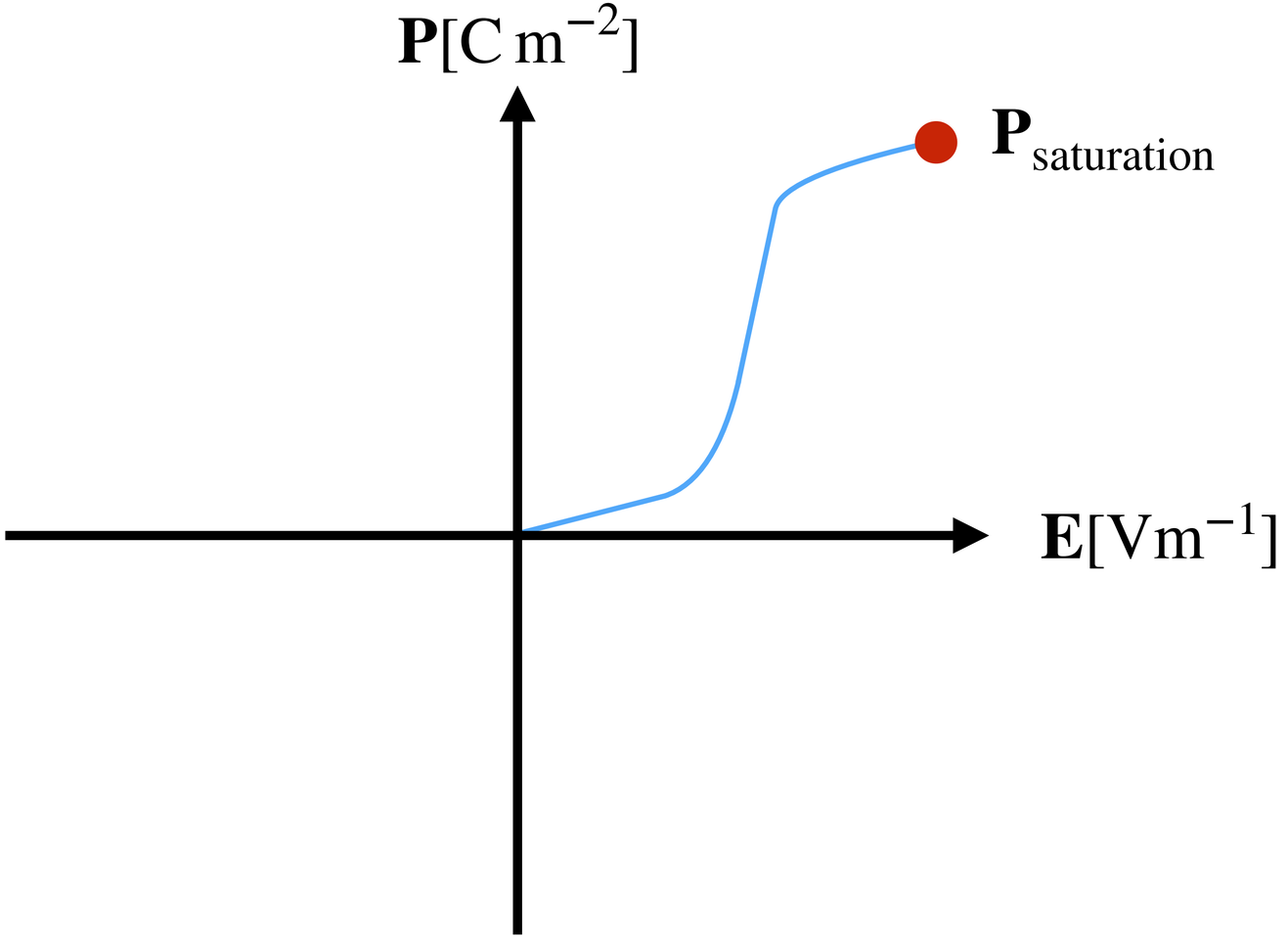
Hysteresis in a “real” ferroelectric



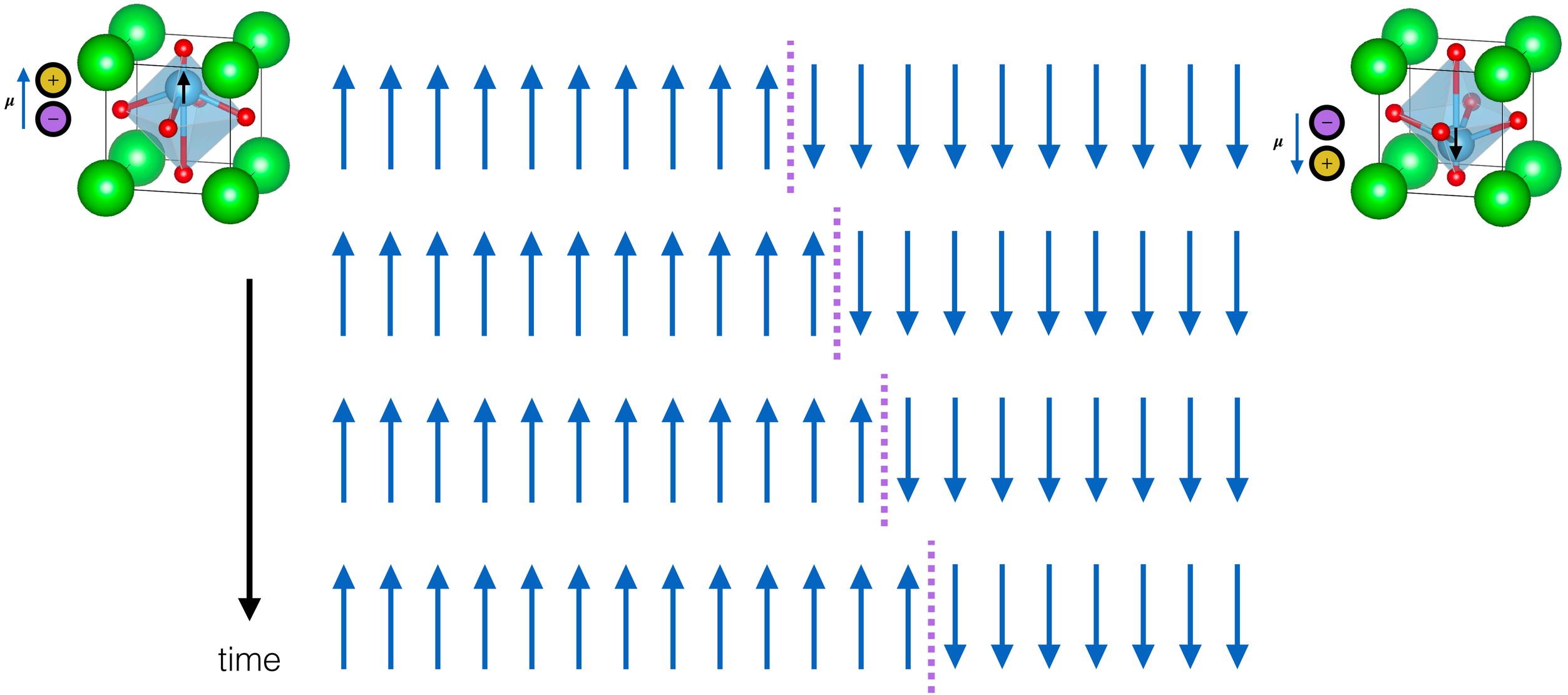


Hysteresis in a “real” ferroelectric





Microscopic motion of domain walls



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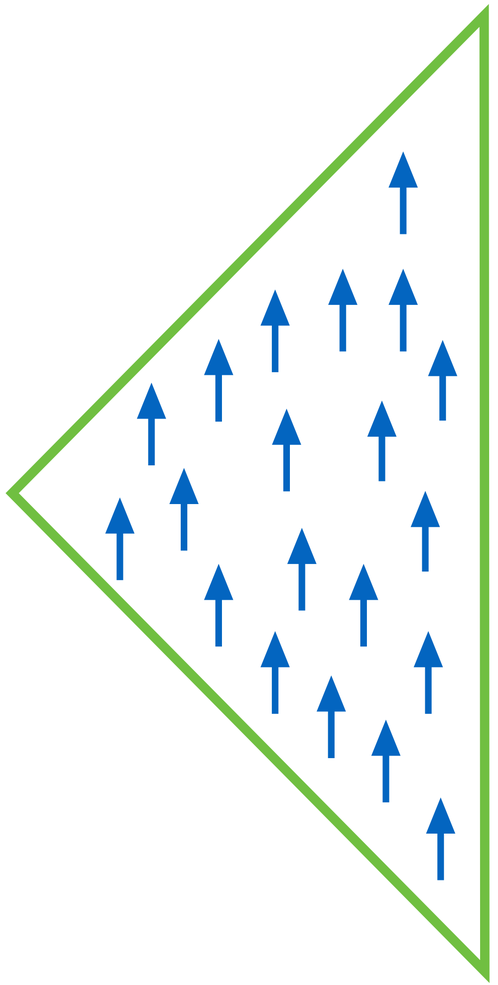

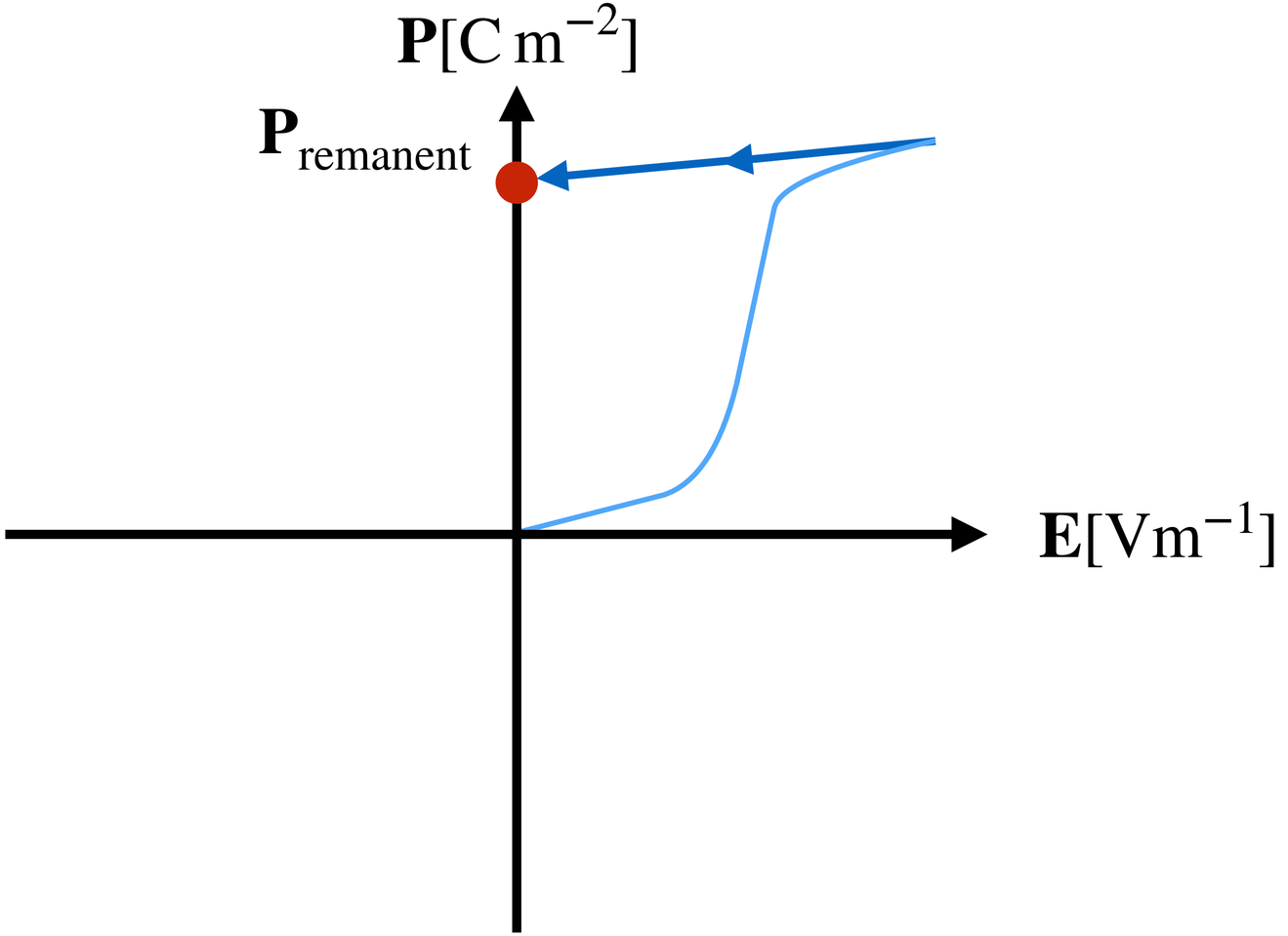

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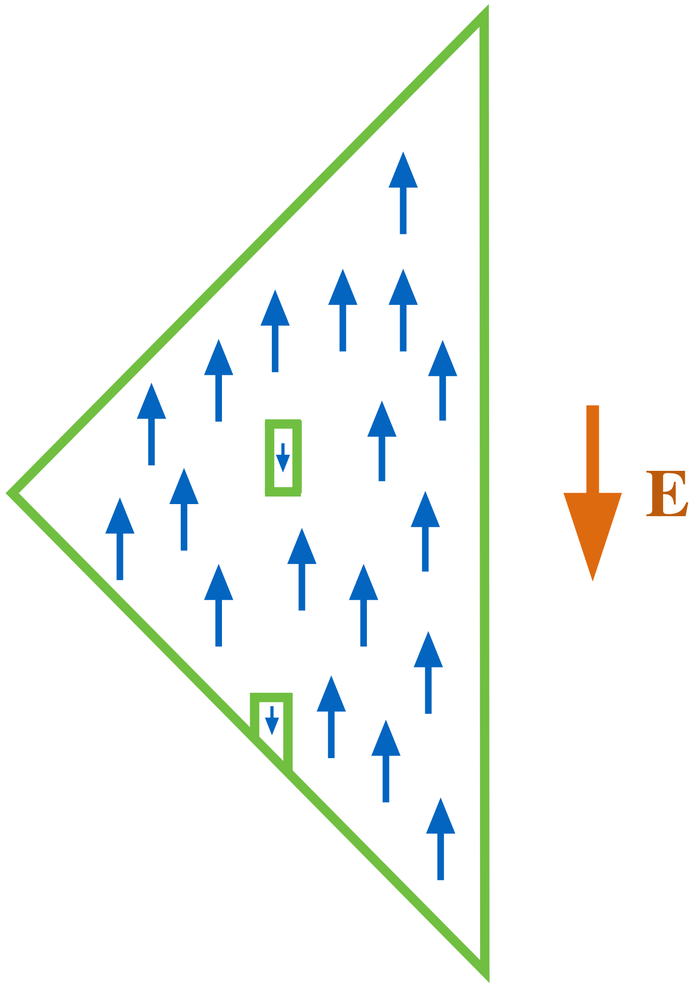
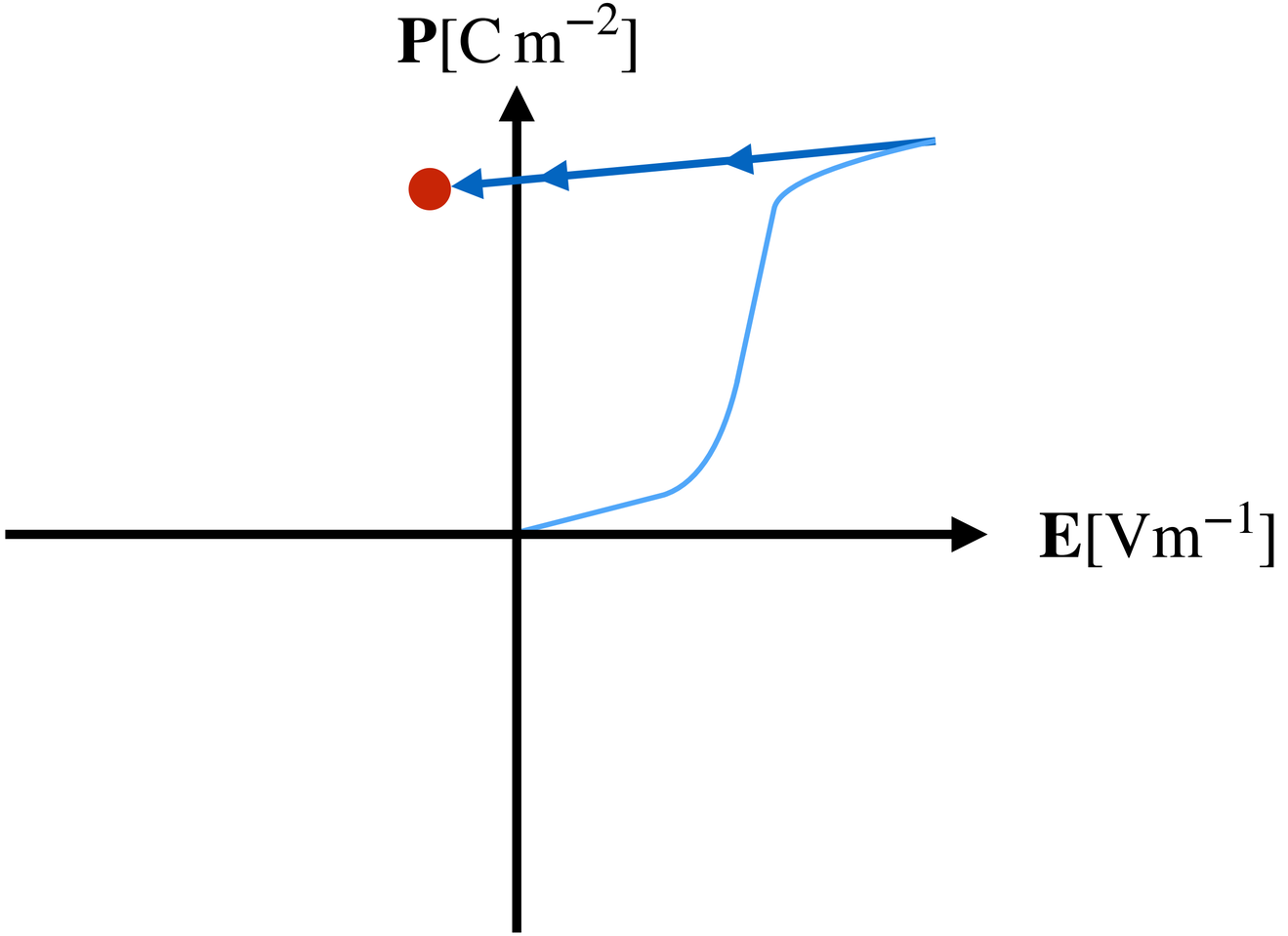
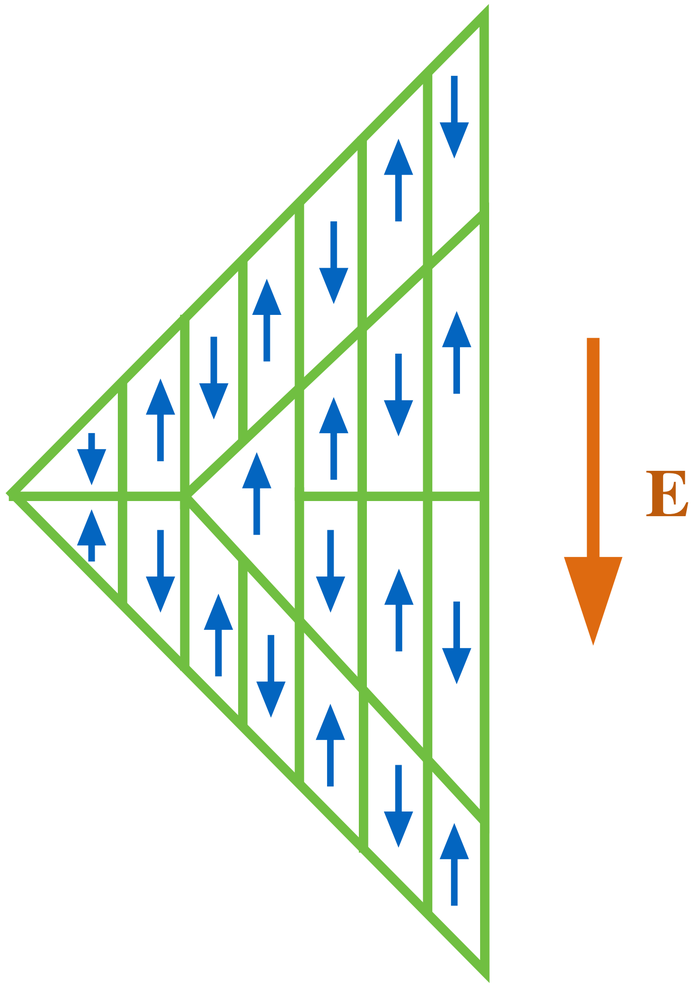
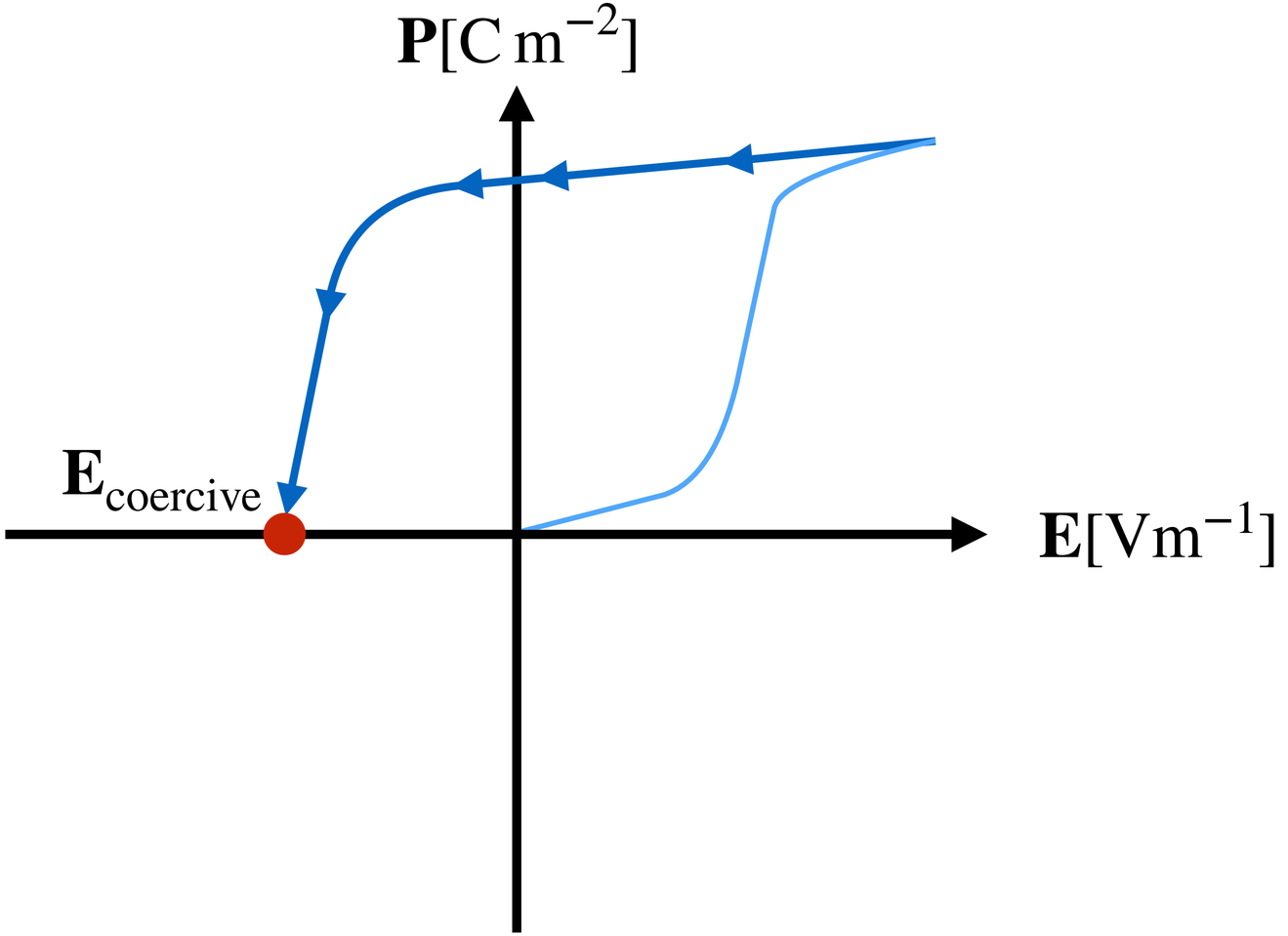


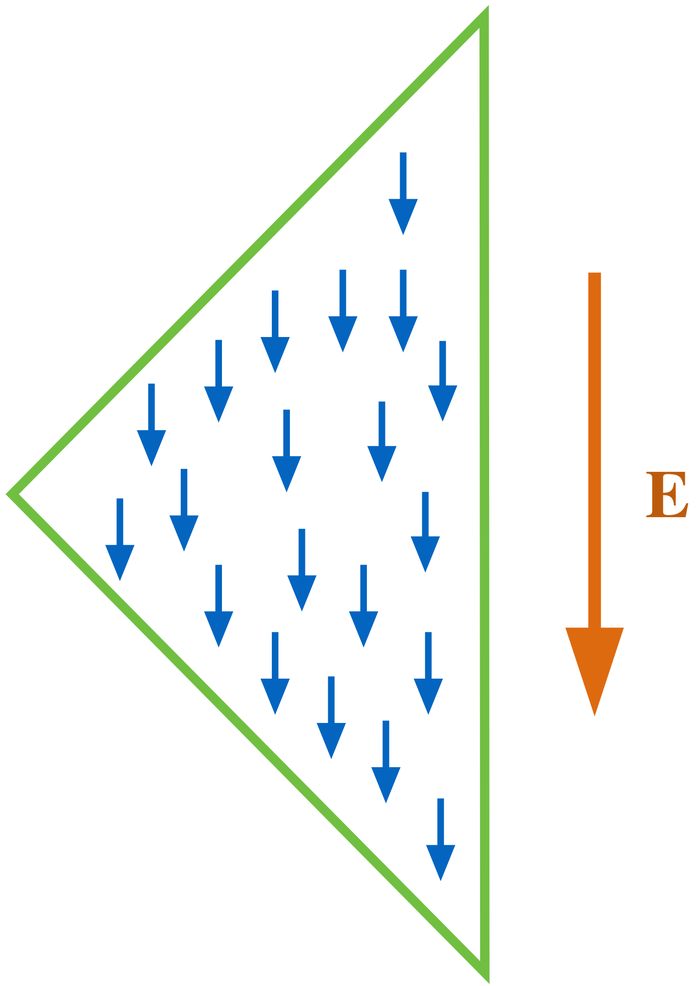


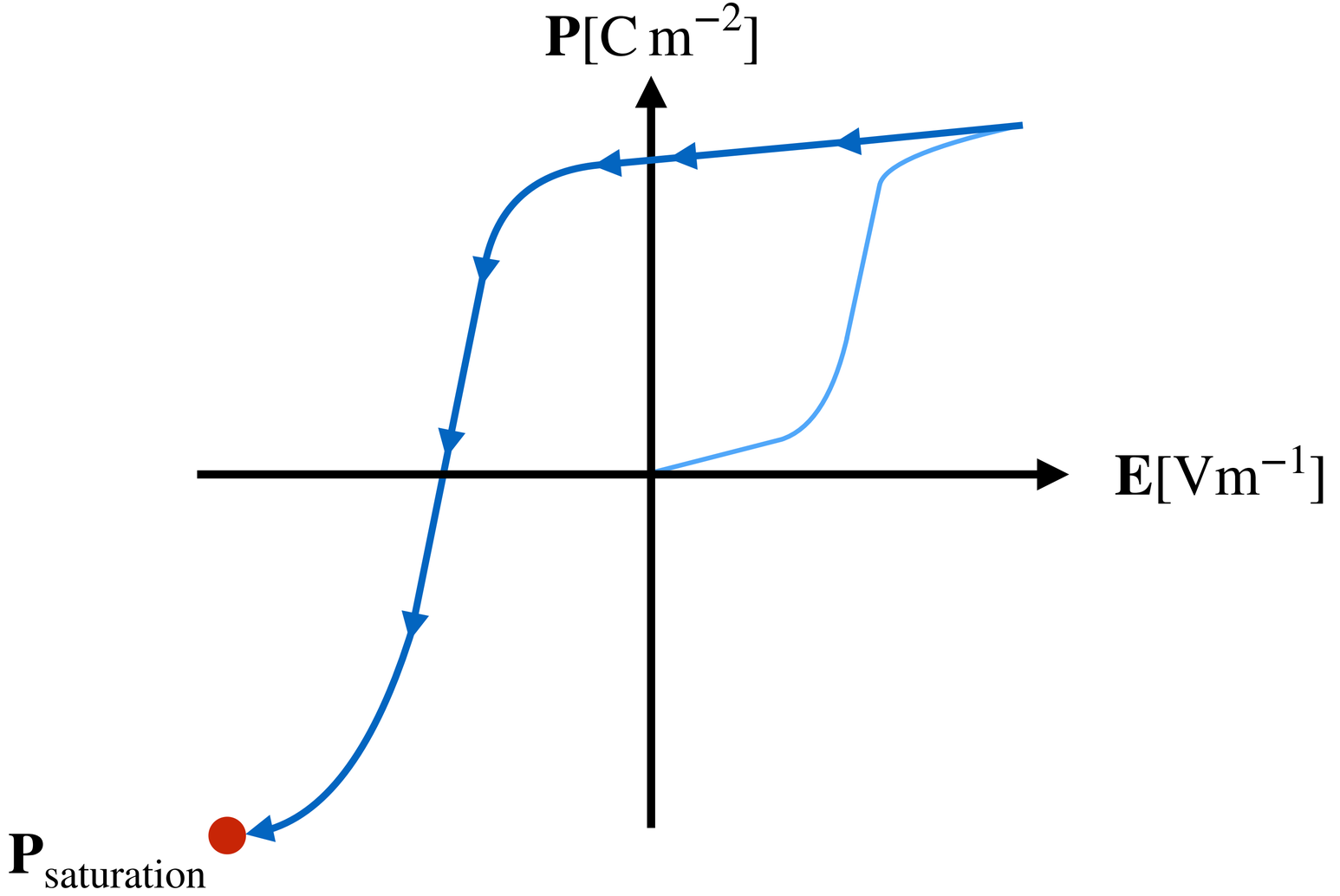
Hysteresis in a “real” ferroelectric



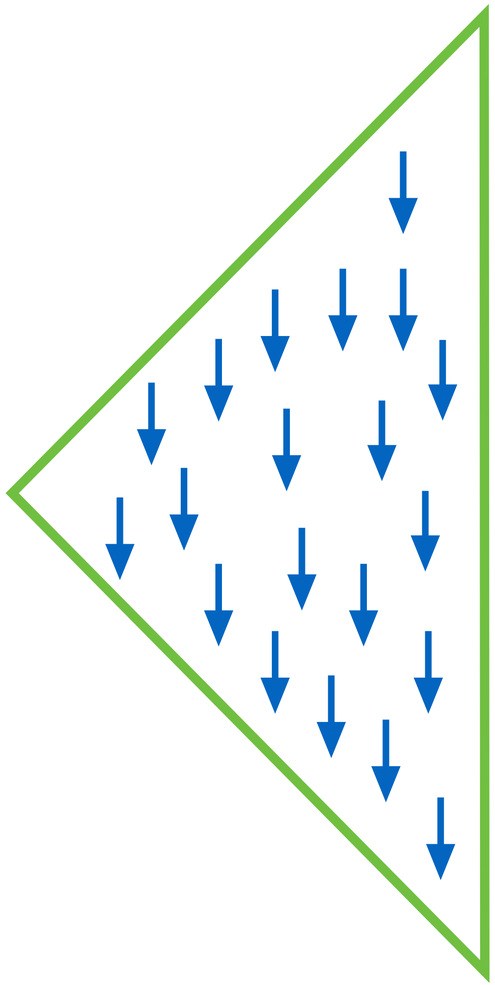


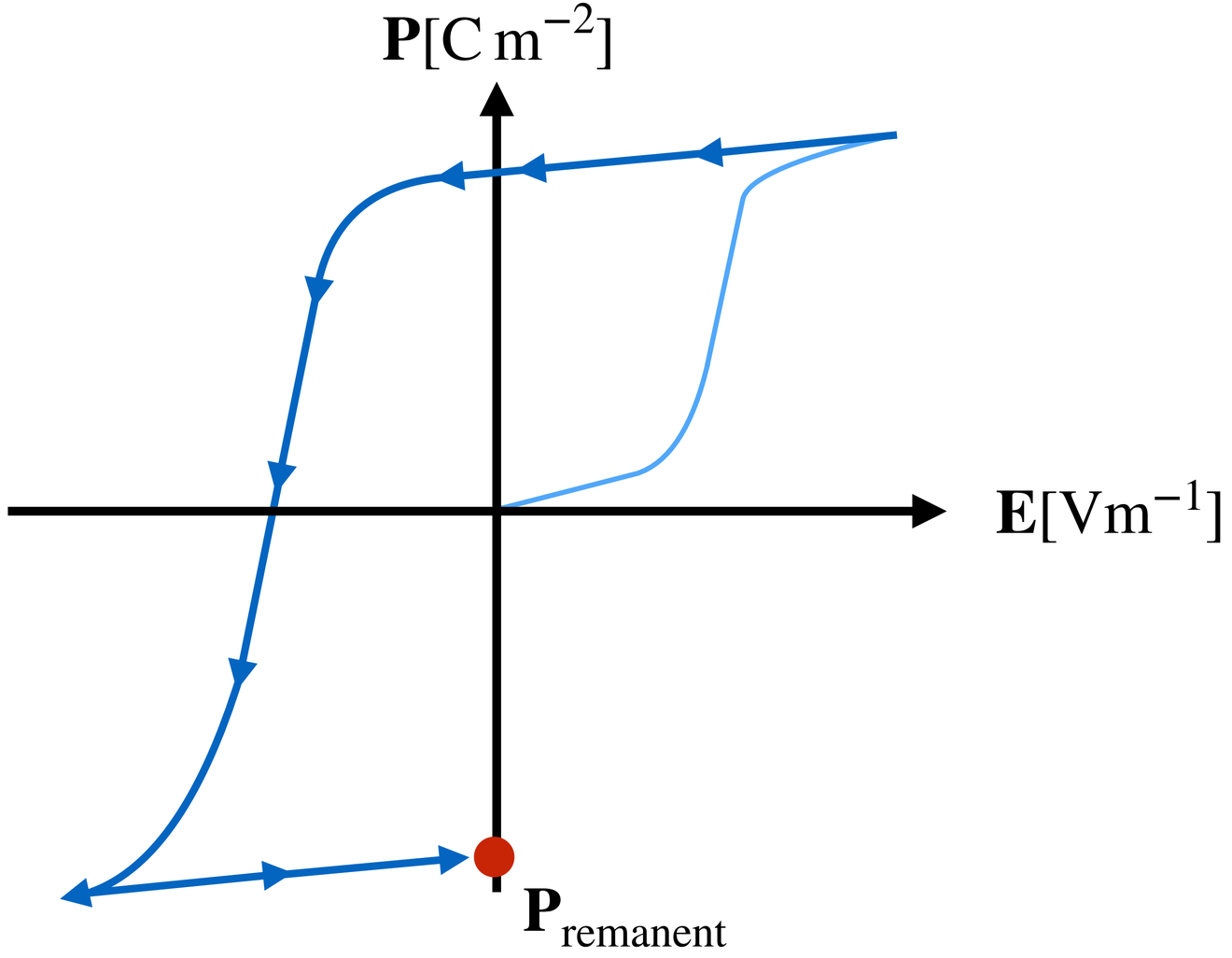
Hysteresis in a “real” ferroelectric



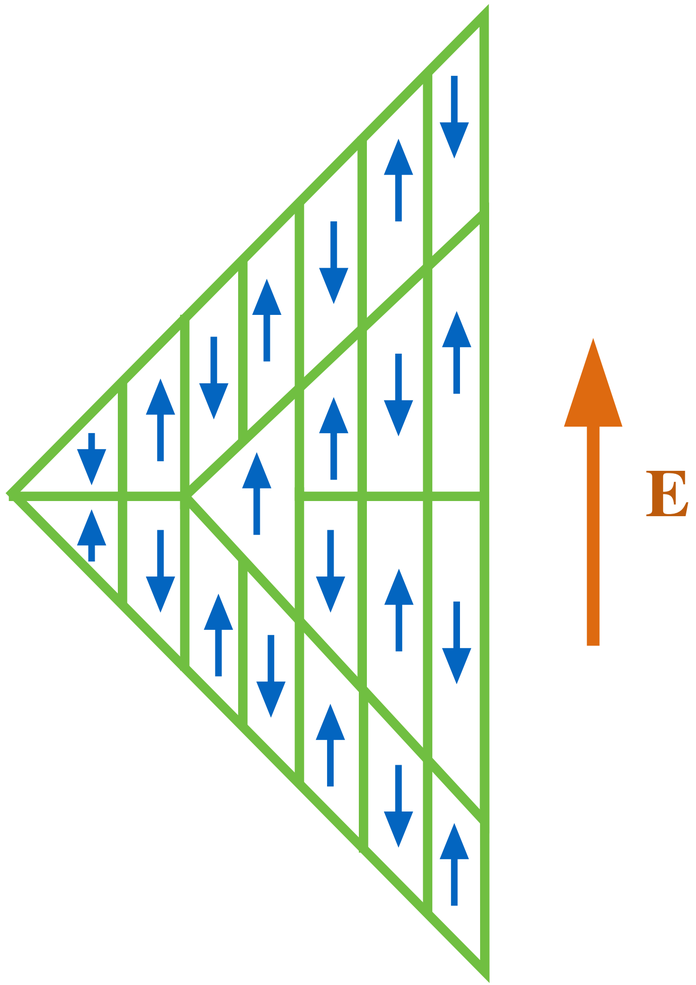


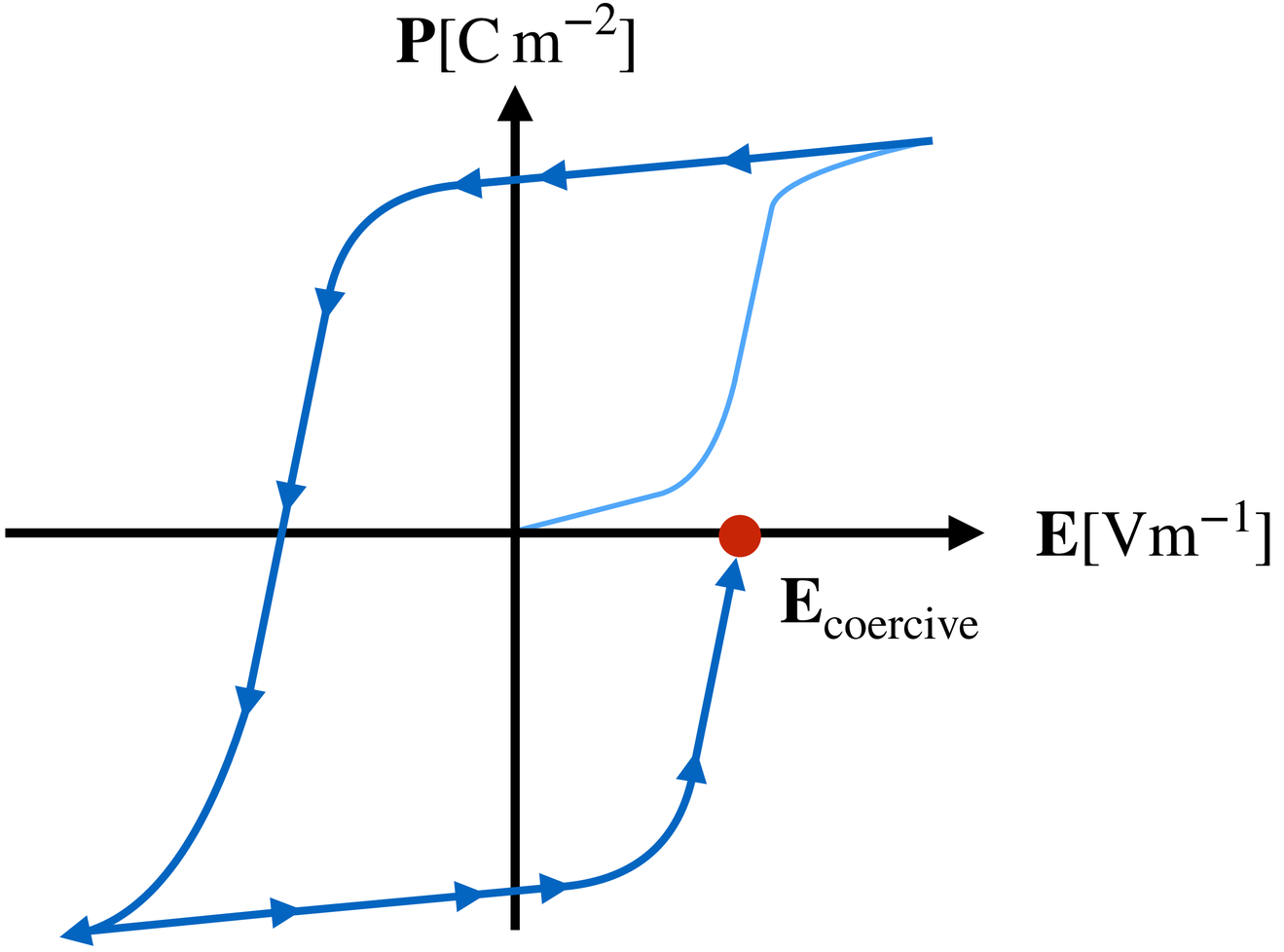
Hysteresis in a “real” ferroelectric



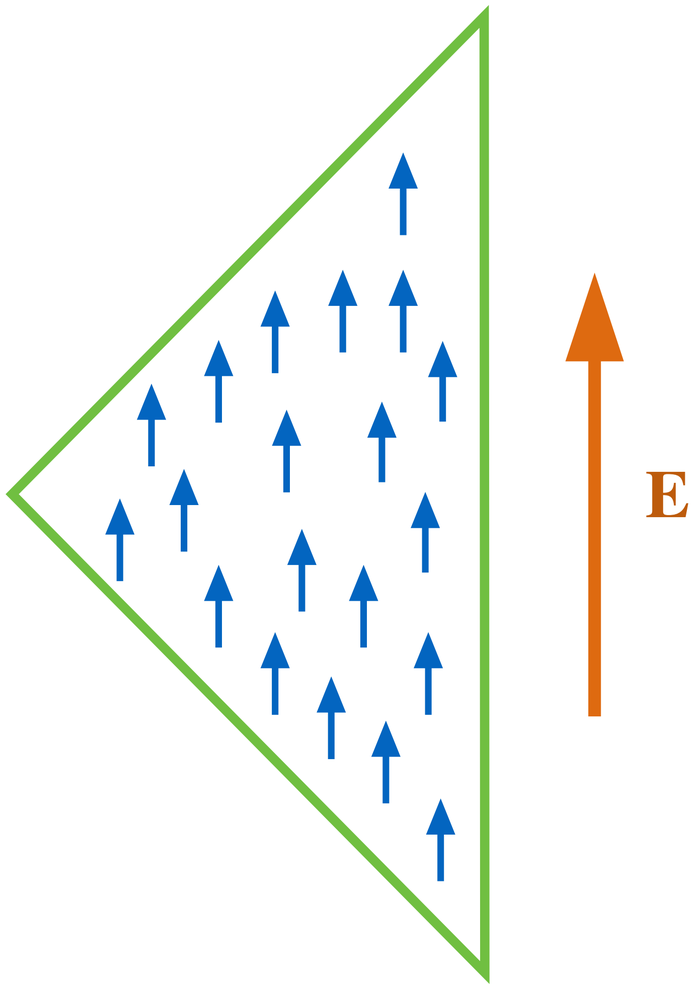


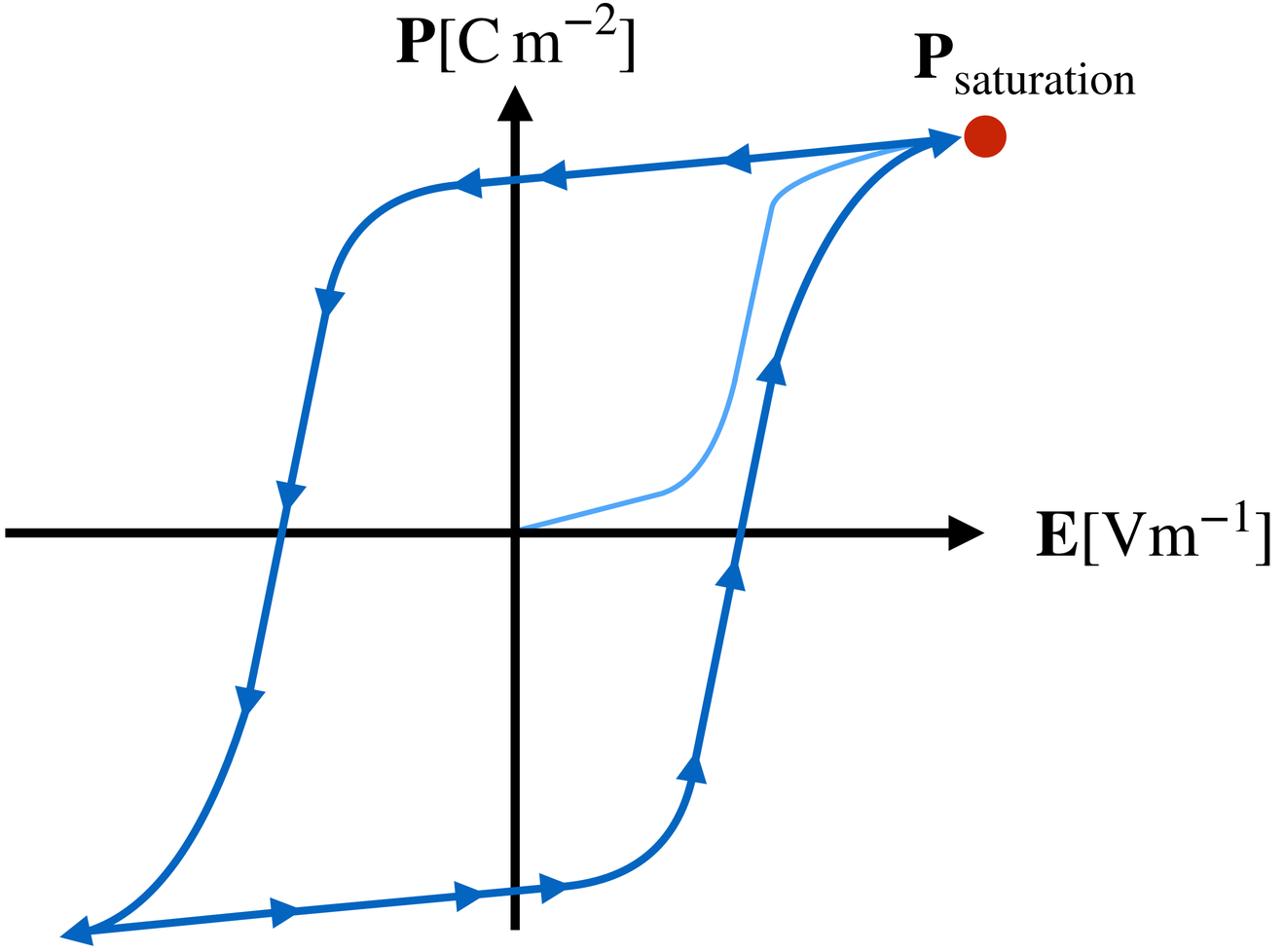
Hysteresis in a “real” ferroelectric



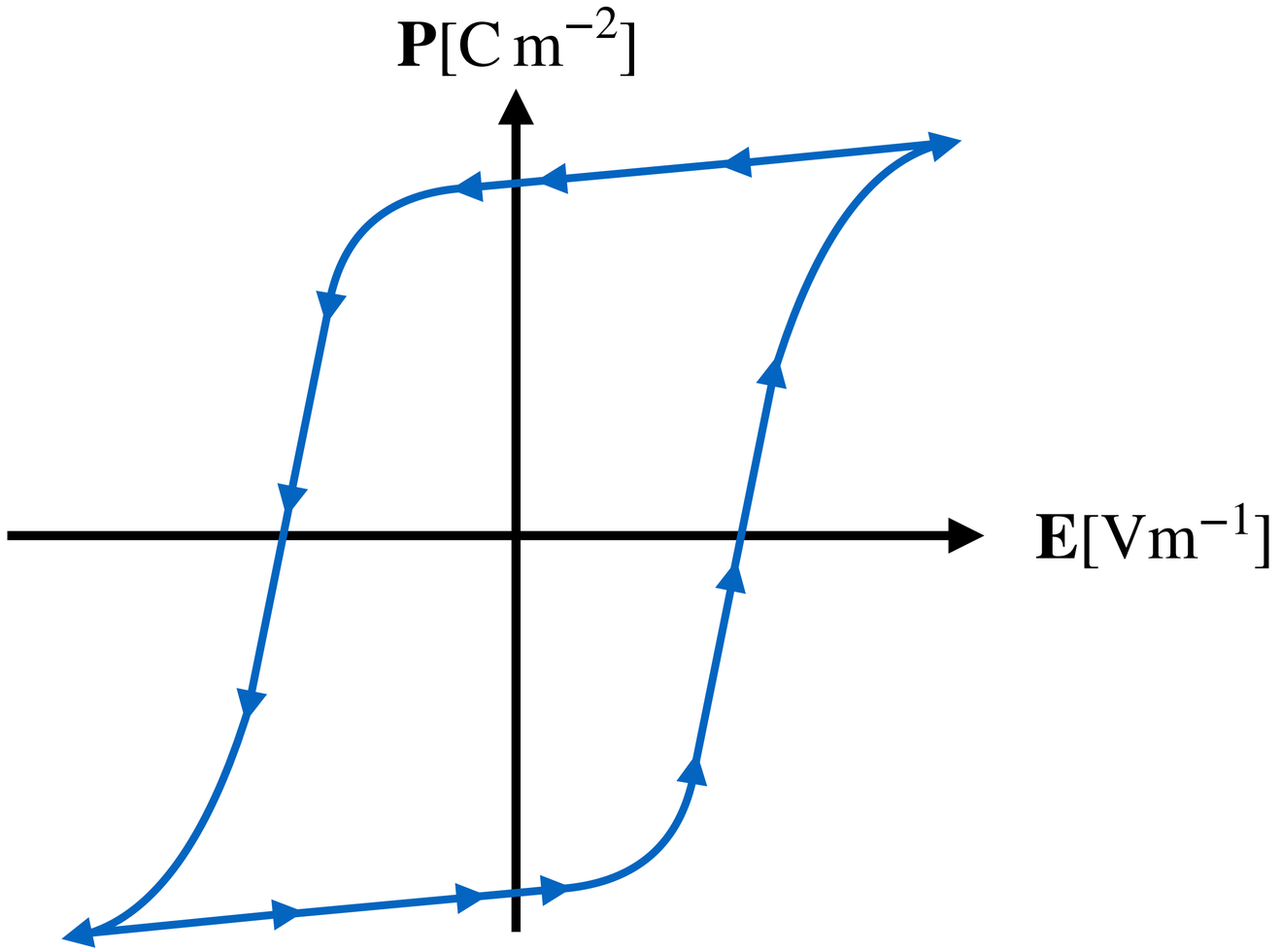


Hysteresis in a “real” ferroelectric

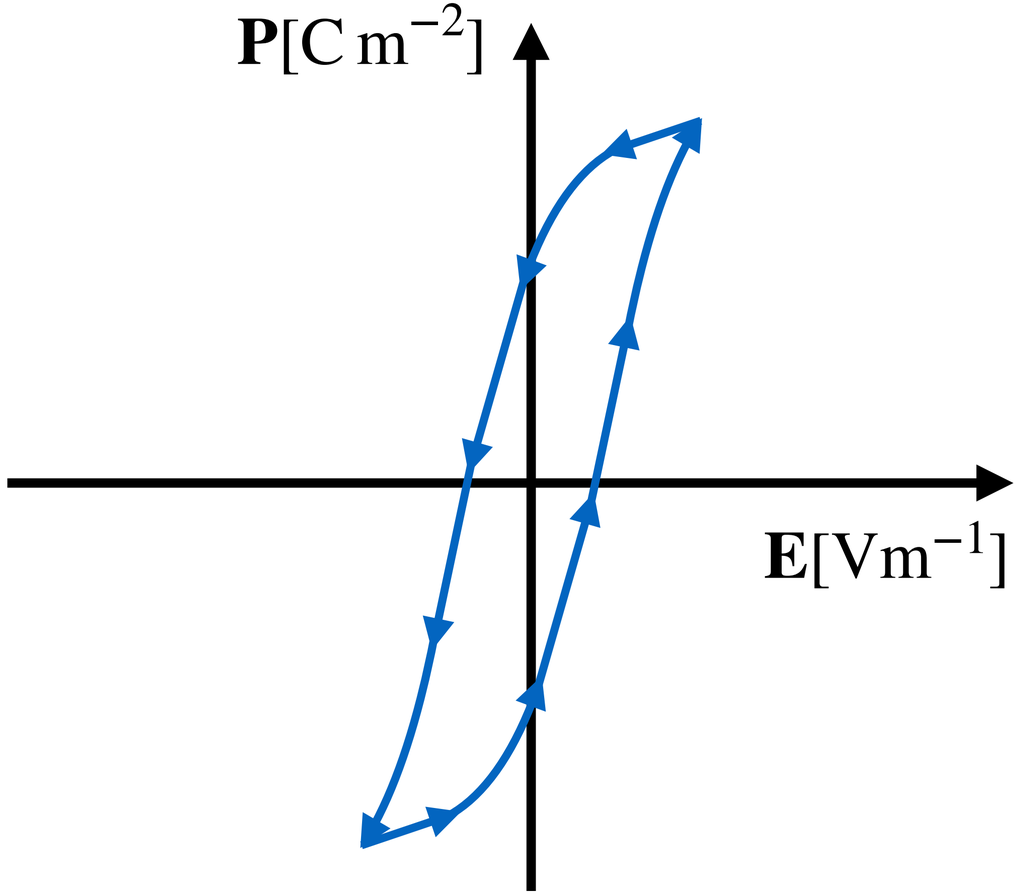


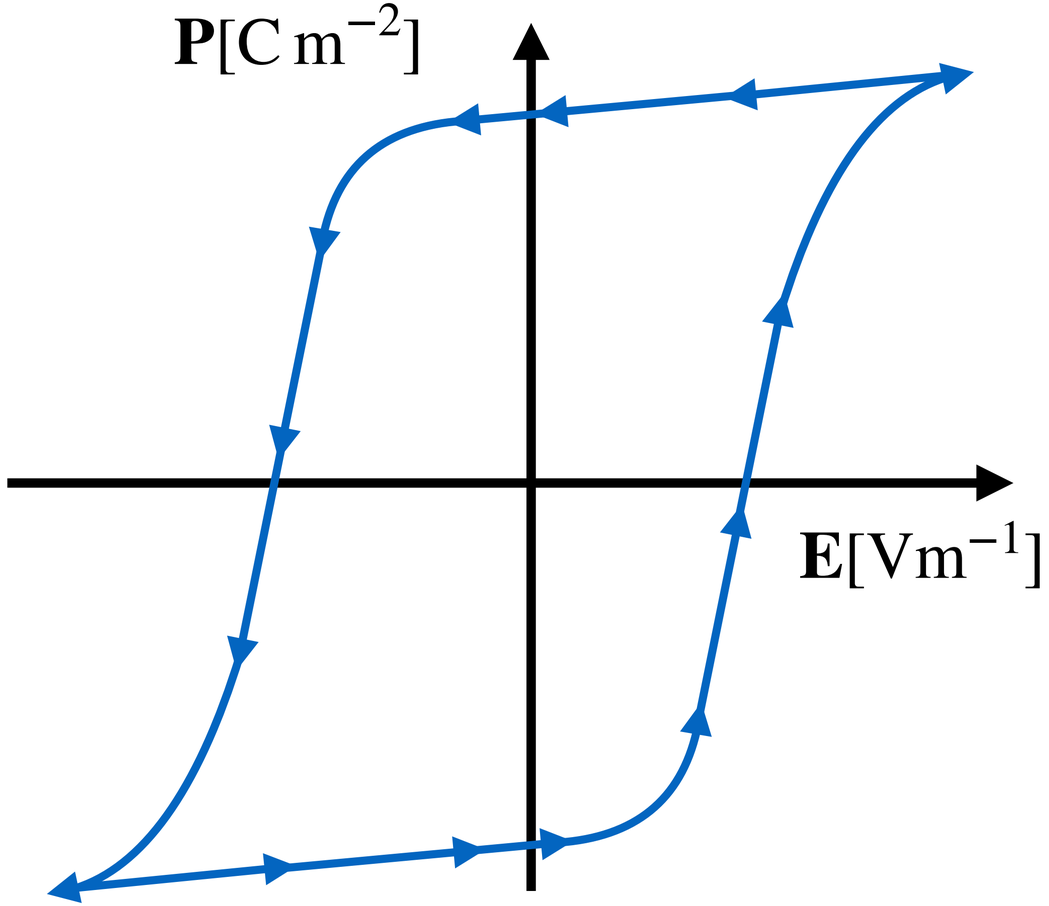


Hysteresis in a “real” ferroelectric

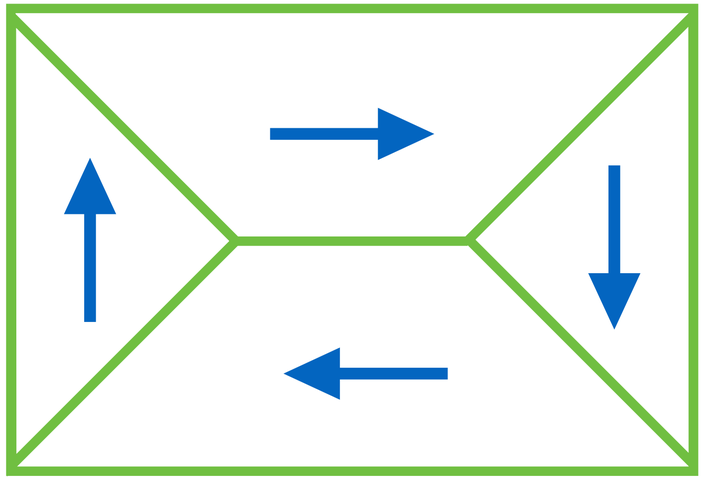


Hysteresis in a “real” ferroelectric

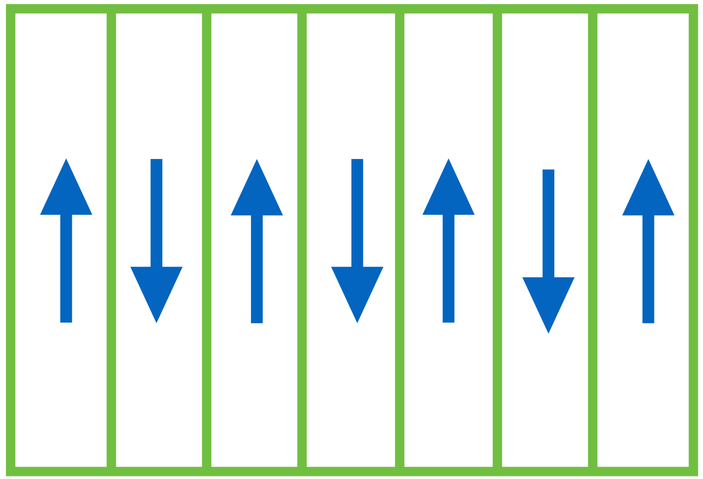




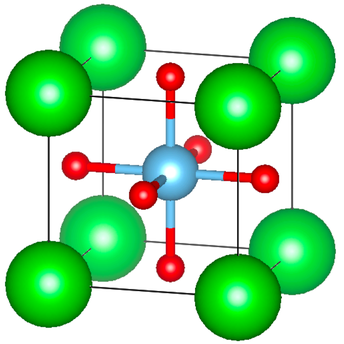
Domains in a single crystal



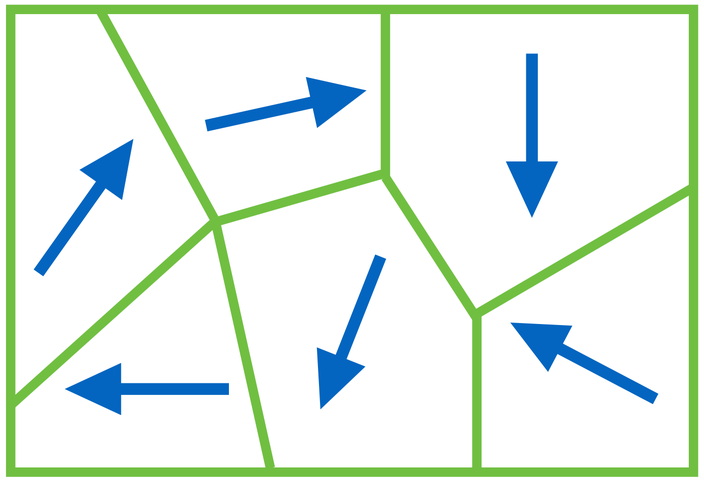
90° domain wall

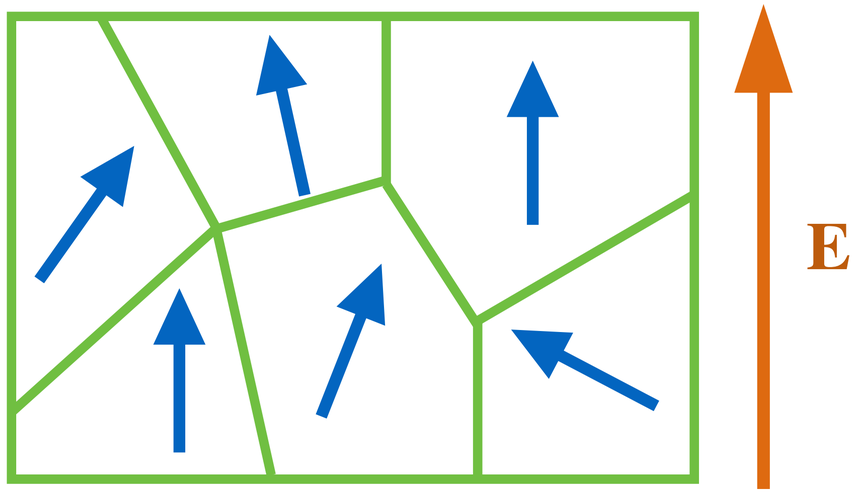


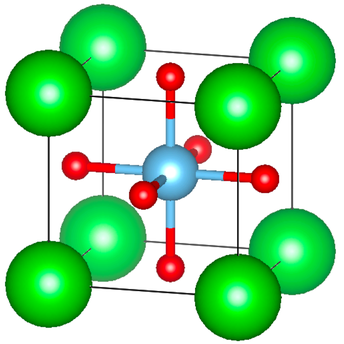
180° domain wall



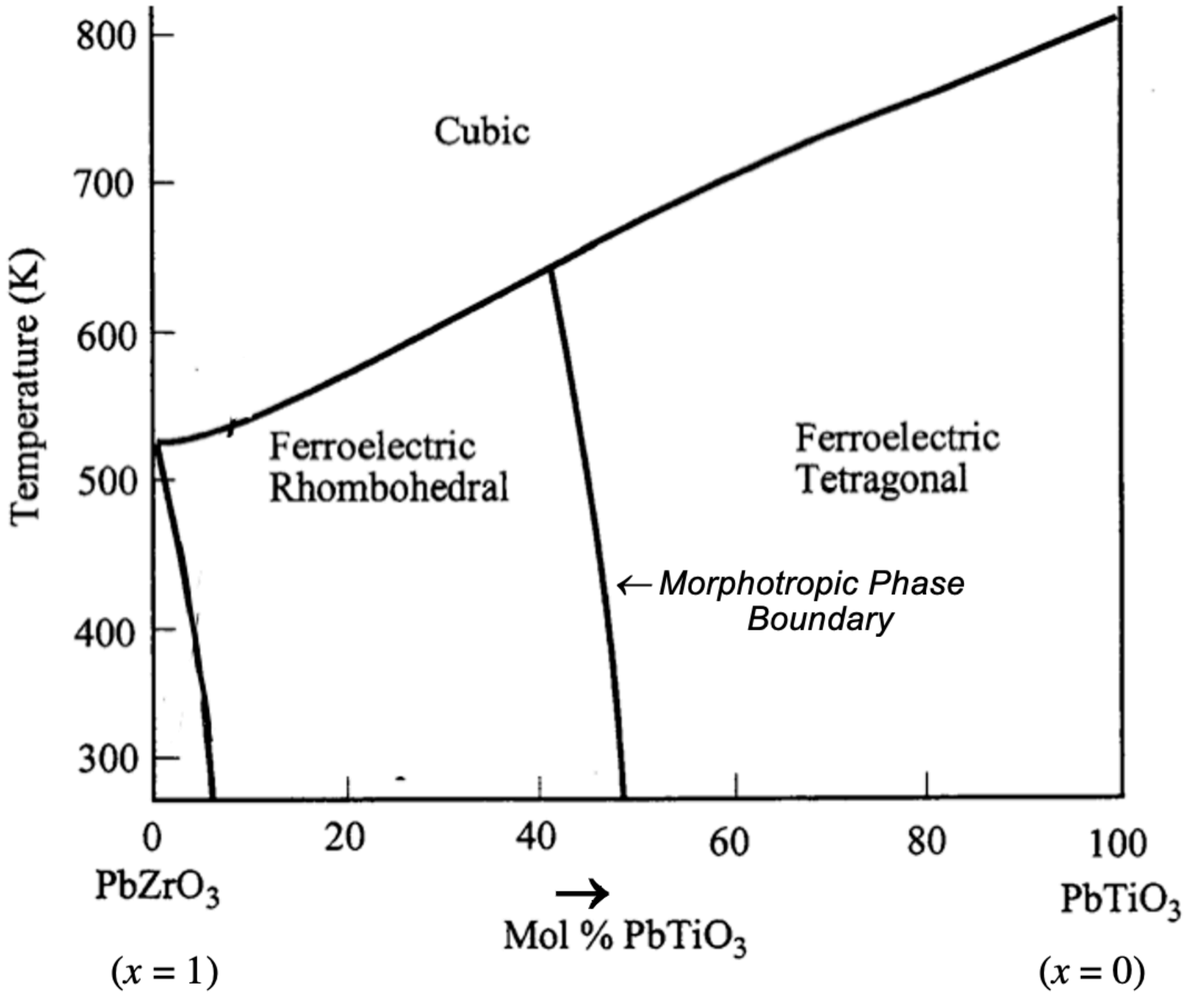
Domains in a polycrystal







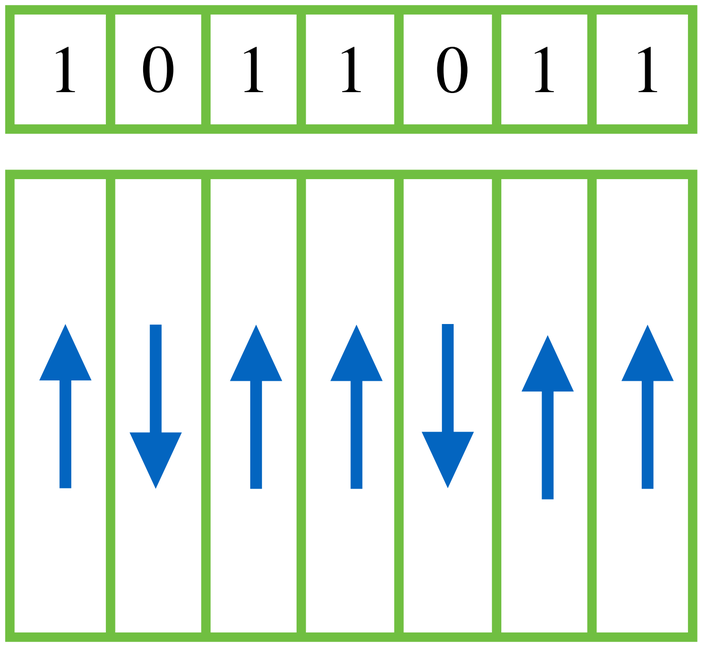
Applications of ferroelectricity: the role of PZT



- PZT: $Pb(Zr_xTi_{1-x})O_3$
- $x \simeq 0.5$: tetragonal-rhombohedral transition
- Can be polarised in 14 directions
- Versatile: used in many applications
- Disadvantage: lead is toxic

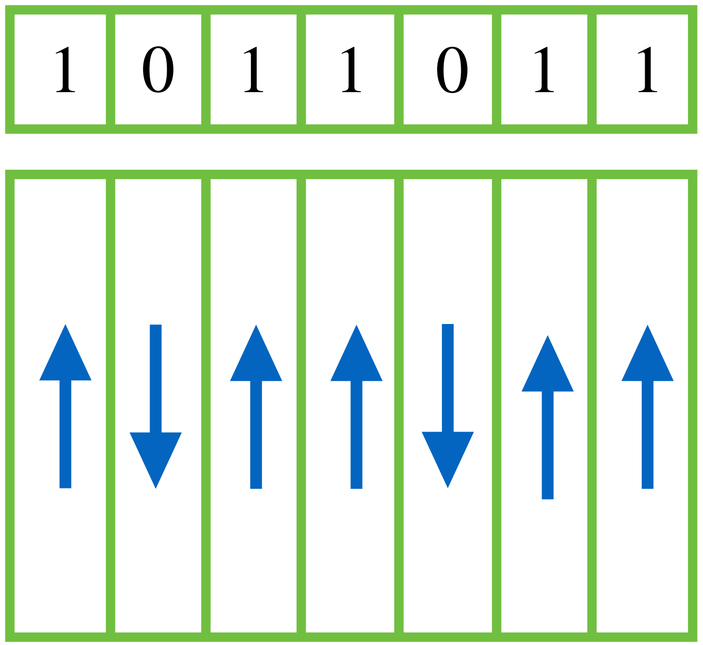
Applications of ferroelectricity: camera flash

Applications of ferroelectricity: memory devices



- **Write to memory**
  - Switch polarisation using electric field
  - Domain nucleation and growth
  - About 50 ns
- **Read from memory**
  - Apply field in direction of 0
  - If nothing happens: state is 0
  - If dipole switches: state is 1
  - If dipole has switched, need to take it back to 0

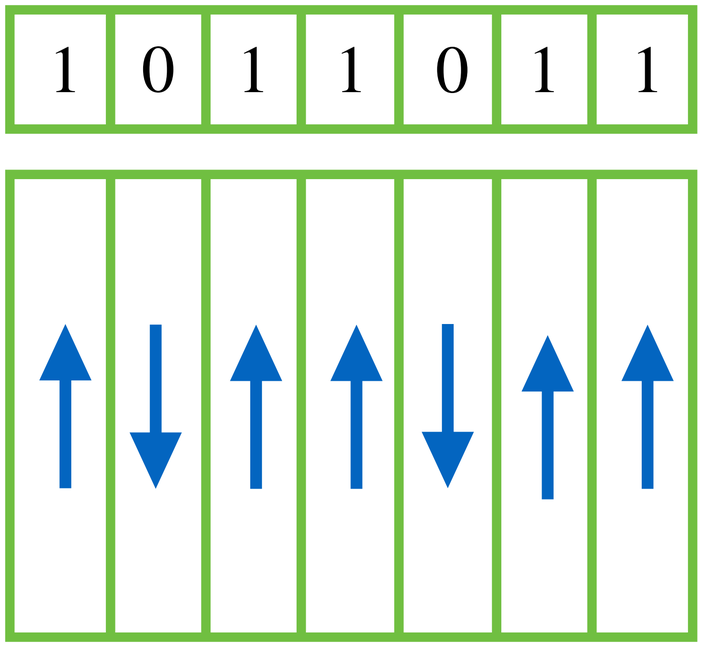
Applications of ferroelectricity: memory devices



- High dielectric constant: sharper transitions between states
- High saturation/remanent polarisation: easy to measure
- Small coercive field: minimise energy required to switch
- (Not too small coercive field: don't want other fields to switch)
- High Curie temperature: resistant to environment changes

e.g. thin films of $LiNbO_3$, $PbTiO_3$, $Pb(Zr_xTi_{1-x})O_3$, $SrBi_2Ta_2O_9$

Applications of ferroelectricity: memory devices

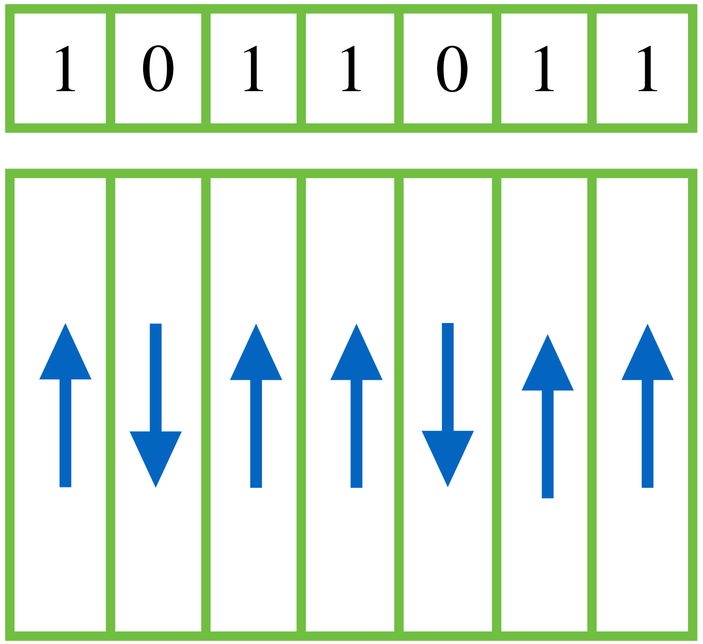


- **Advantages:**
  - Non-volatile (very stable)
  - Low voltage
  - Fast switching
  - Radiation resistant
- **Disadvantages:**
  - Low storage density
  - High cost

Flash memories became the technology of choice

FE-RAM are used in niche applications

Applications of ferroelectricity: memory devices



FUJITSU FUJITSU SEMICONDUCTOR MEMORY SOLUTION

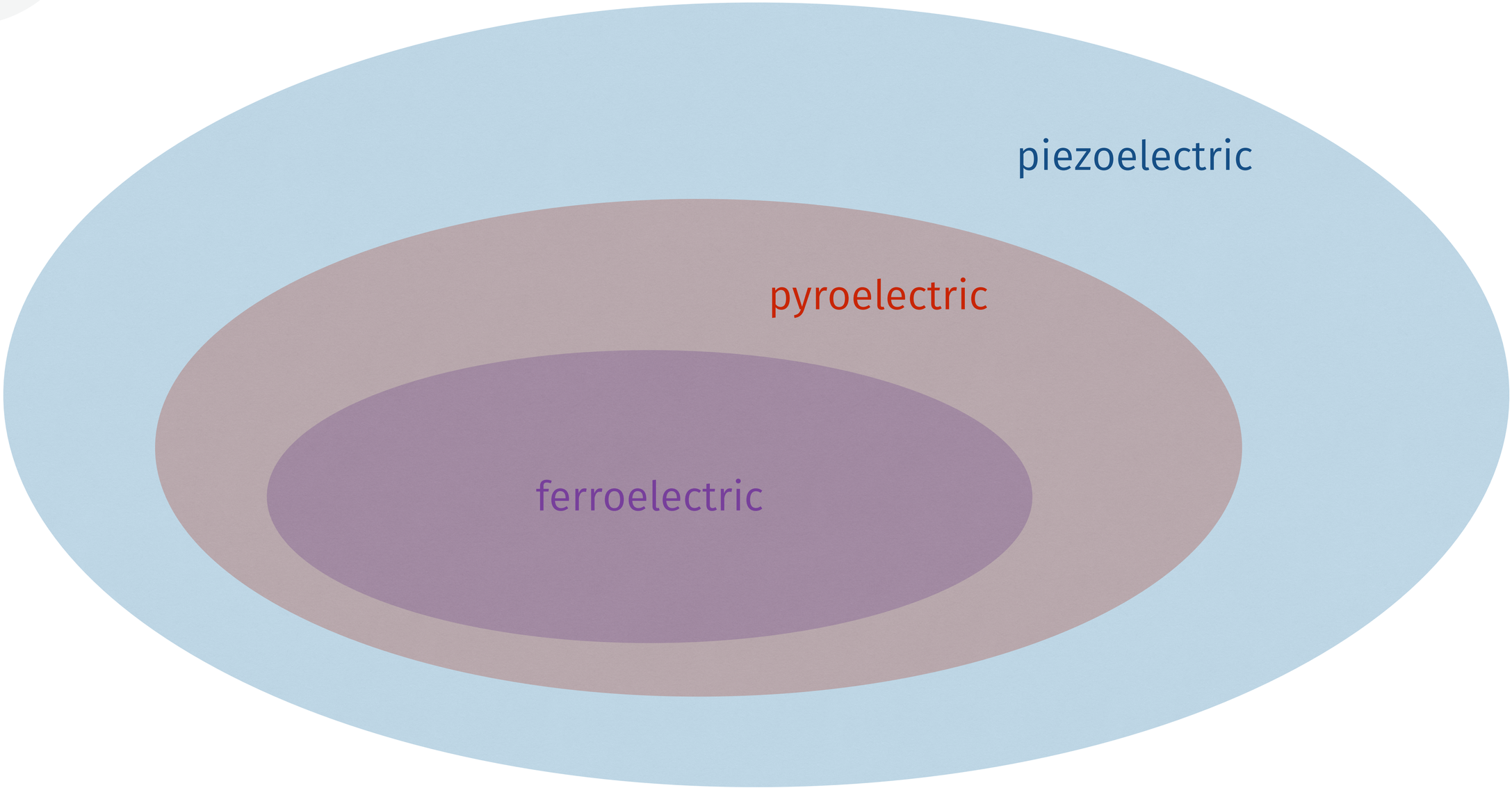
Smart Watches

- Use case:
  Real-time data logging of GPS information
- Why FeRAM?:
  Low power consumption at writing, Fast write speed

CT Scan

- Use case:
  Record of precise position information for scanning device, Storage of parameter information
- Why FeRAM?:
  Non-volatility, 10 trillion read/write endurance, Fast write speed

https://www.fujitsu.com/jp/group/fsm/en/products/feram/application/


piezoelectric
pyroelectric
ferroelectric