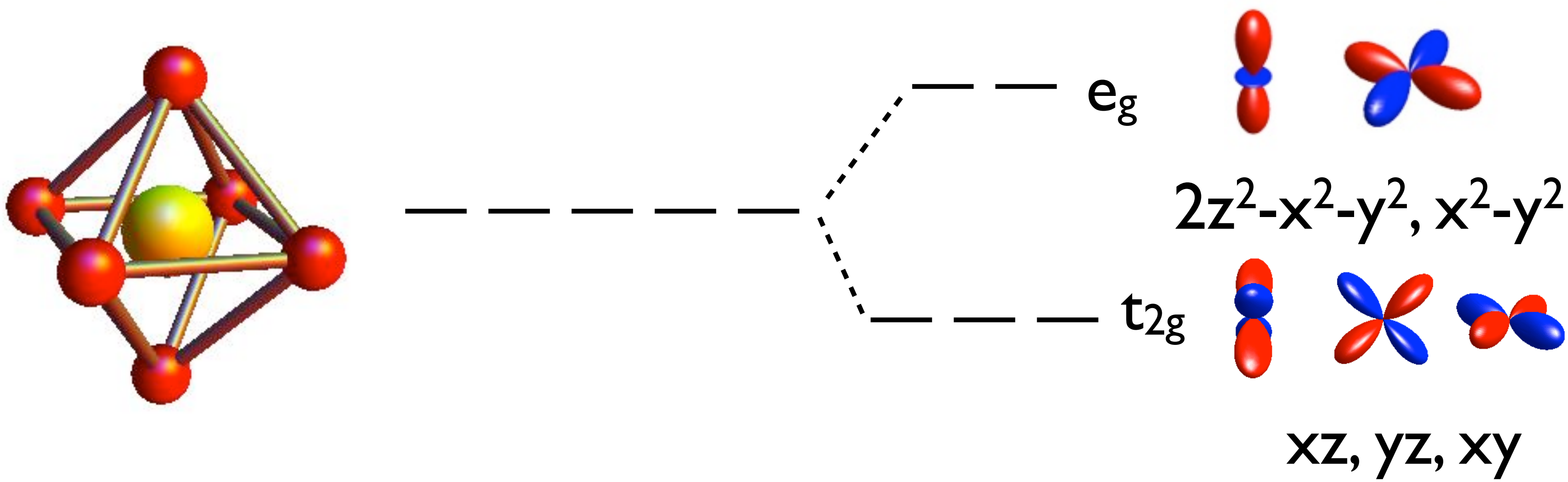
Moments in Solids

- Example: cubic crystal field for a metal atom in an oxygen octahedron



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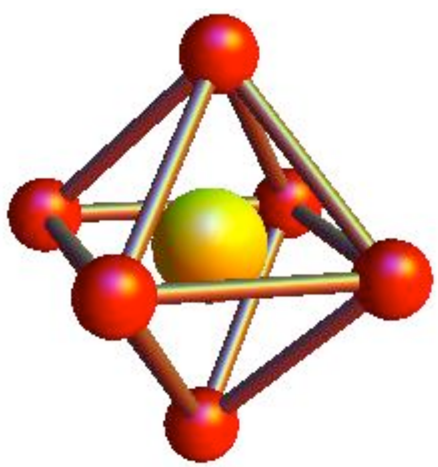

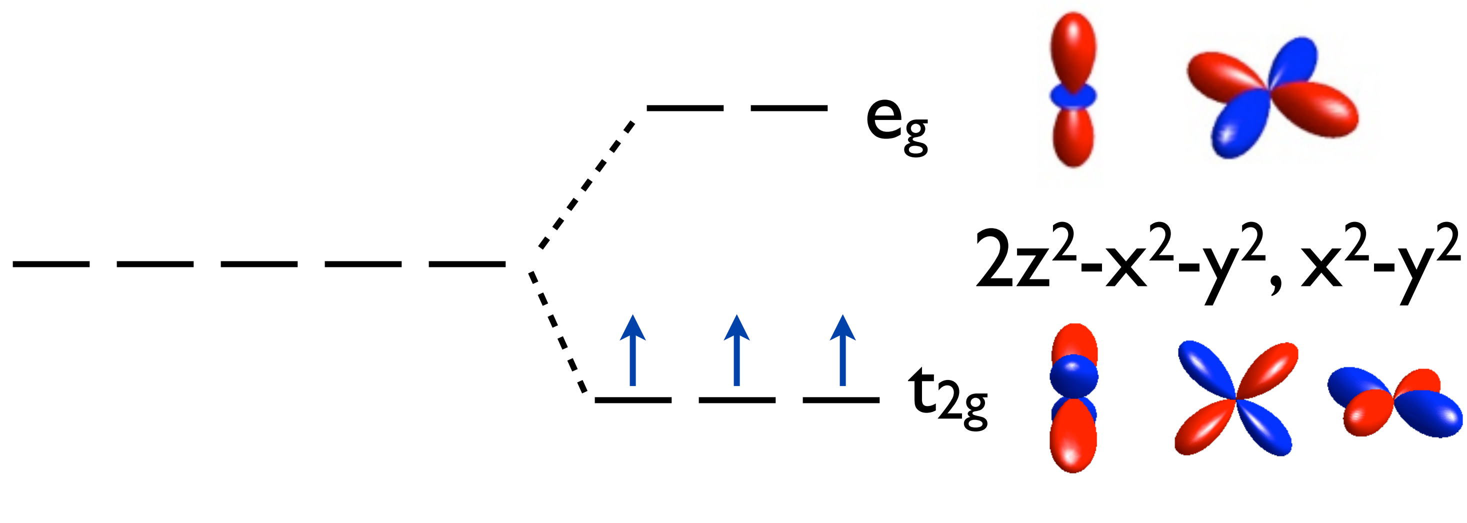

xz, yz, xy

e.g.
$Cr^{3+}=3d^3$

S=3/2, L=0

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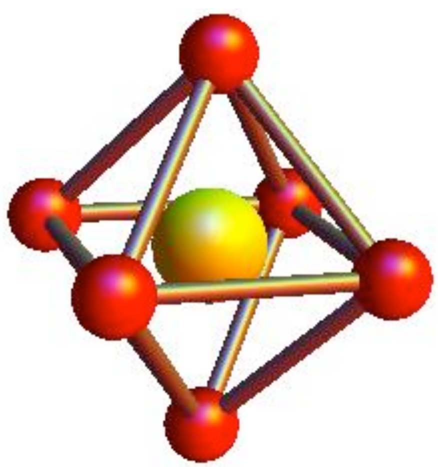
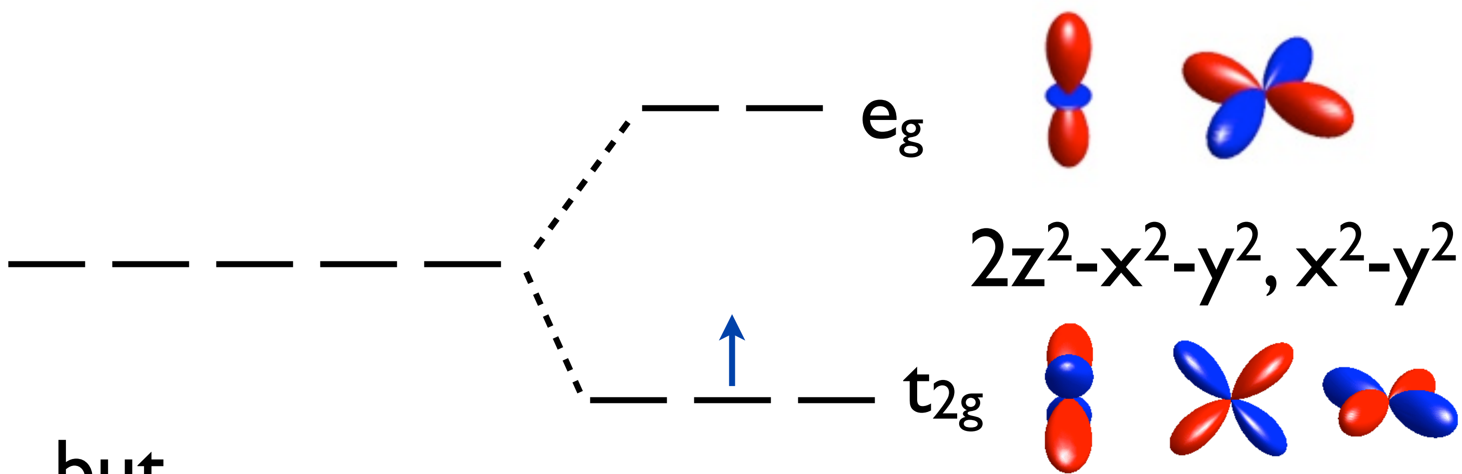




xz, yz, xy

but
Ti^{3+}=3d^1 is
more
complicated

S=1/2, L_{eff}=1
"orbital degeneracy"

Local moments

- Local moments are *not* part of band theory
  - Works in materials where electrons are localized to atoms, and delocalization is prevented somehow -- insulators
  - Such materials, which have partially filled shells but are insulating, are called Mott insulators
- How do we know they exist?

Curie Susceptibility

- Existence of local moments means degenerate states
  - By application of a small magnetic field, this degeneracy is split and a particular spin state is selected
  - Expect large susceptibility $\chi = \partial M / \partial H|_{H=0}$

Curie Susceptibility

- Magnetic moment in general is proportional to spin

$$\boldsymbol{\mu} = g\mu_B \mathbf{S}/\hbar$$

spin S quantum spin
$S^2=S(S+1)\hbar^2$

g-factor
(could be a tensor)
$g \approx 2$ for pure spin moment

Bohr magneton

$$\mu_B = \frac{e\hbar}{2m_e} = 9.3 \times 10^{-24} J/T$$
$$= 0.671 K/T$$

- Magnetic dipole interaction

$$\mathcal{H} = -\boldsymbol{\mu} \cdot \mathbf{H}$$

Curie Susceptibility

- Thermodyamics $M = -\frac{\partial F}{\partial H}$ $F = -kT \ln Z$

$$Z = \sum_n e^{-E_n/kT}$$

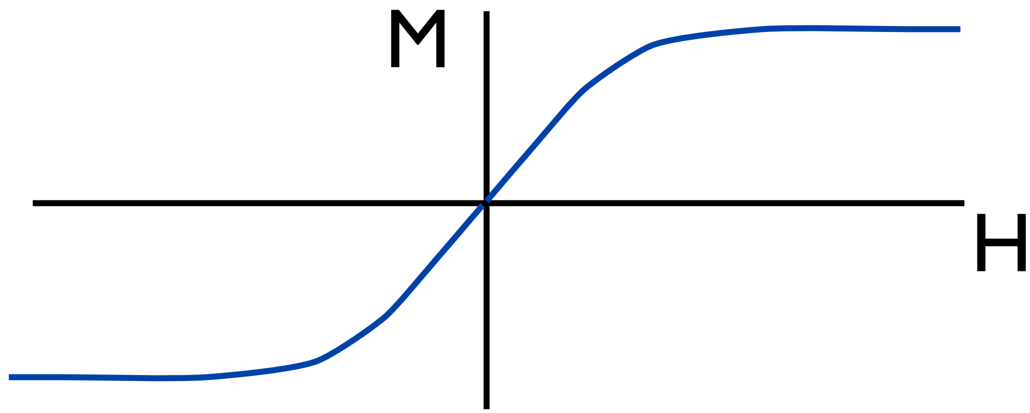
- For example, S=1/2 $E_{\uparrow/\downarrow} = \mp g\mu_B H/2$

$$Z = 2\cosh\left(\frac{g\mu_B H}{2kT}\right) \qquad M = \frac{g\mu_B N}{2}\tanh\left(\frac{g\mu_B H}{2kT}\right)$$

Curie Susceptibility

- Magnetization

$$M = \frac{g\mu_B N}{2} \tanh\left(\frac{g\mu_B H}{2kT}\right)$$



- Susceptibility

$$\chi = \frac{(g\mu_B)^2 N}{4k_B T} = \frac{A}{T}$$

Curie Law:
indicates local moment

Curie Susceptibility

- Thermodyamics

$$M = -\frac{\partial F}{\partial H} \qquad F = -kT \ln Z$$

$$Z = \sum_n e^{-E_n/kT}$$

- General result

$$\chi = \frac{N(g\mu_B)^2}{3} \frac{S(S+1)}{kT}$$

plot χ^{-1} versus T to extract "effective moment"

Contrast with metals

Curie Law

$$\chi = \frac{N(g\mu_B)^2}{3}\frac{S(S+1)}{kT}$$

Pauli paramagnetism

$$\chi = V\frac{(g\mu_B)^2}{4}D(\epsilon_F)$$

basically kT → ε_F

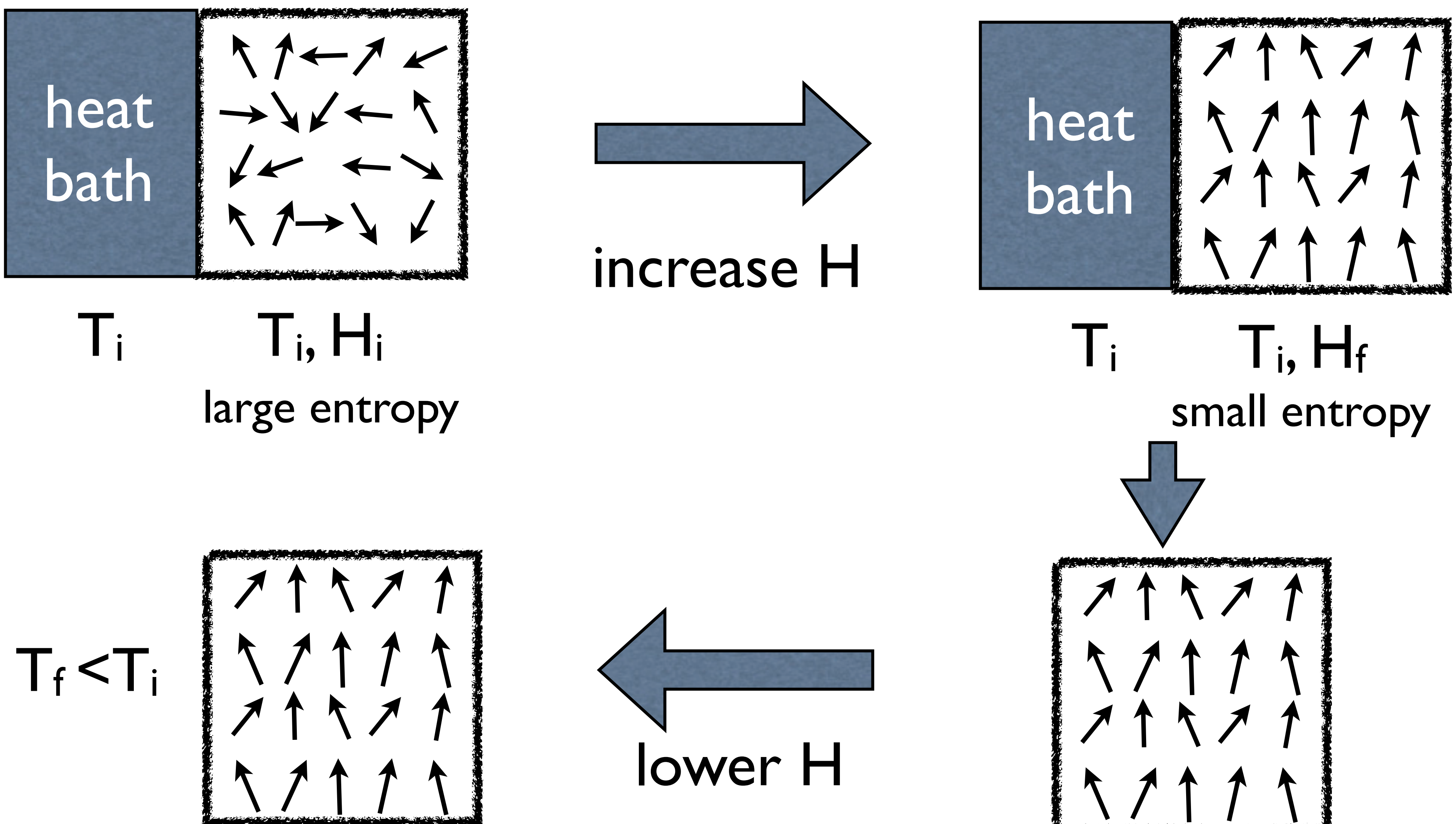
Does χ really diverge for local moments?

NO, because they interact

Magnetic cooling

- The large susceptibility of free spins at low temperature means they are easily aligned by small magnetic fields
- This alignment corresponds to a drastic reduction of entropy. One can use this control over entropy to remove entropy from another system, thereby cooling it.

Magnetic Cooling



Magnetic Cooling

- A→ B: isothermal step - raise field, lower entropy
- B→ C: adiabatic step - lower field, same entropy: lower temperature
- For paramagnetic spins, S = S(H/T)
  - Hence $H_1/T_f = H_2/T_i$