Magnetic Order

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Simple ferromagnetic, antiferromagnetic and ferrimagnetic order

ferro  antiferro  ferri
Two sublattices

| A B A B A B | ↑↓↑↓↑↓ |
| B A B A B A | ↓↑↓↑↓↑ |
| A B A B A B | ↑↓↑↓↑↓ |
| B A B A B A | ↓↑↓↑↓↑ |

Binary alloy  antiferromagnet
Magnetite $\text{Fe}_3\text{O}_4$

The structural formula for magnetite is

$$[\text{Fe}^{3+}]_A [\text{Fe}^{3+},\text{Fe}^{2+}]_B \text{O}^2_-\text{O}_4^-$$

This particular arrangement of cations on the A and B sublattice is called an inverse spinel structure. With negative AB exchange interactions, the net magnetic moment of magnetite is due to the B-site Fe$^{2+}$. 
Two ways of partial compensation

Unbalanced antiferromagnet

Cohabitation of ferro- and antiferromagnet

The modern phase of magnetic studies began with the use of neutron diffraction to explore magnetic structures.

Spin-density-wave antiferromagnetism in chromium

The beauty and mystery of Cr
Three sublattices

<table>
<thead>
<tr>
<th>C A B C A B</th>
<th>↑↑↓↑↑↓</th>
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<tbody>
<tr>
<td>A B C A B C</td>
<td>↑↓↑↑↓↑</td>
</tr>
<tr>
<td>B C A B C A</td>
<td>↓↑↑↑↓↑</td>
</tr>
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<td>C A B C A B</td>
<td>↑↑↓↑↑↓</td>
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A tetrahedral, occupied by Fe$^{3+}$
B and C octahedral, B occupied by Fe$^{3+}$, C occupied by Fe$^{2+}$
MnO, a "simple" antiferromagnet

1949, Shull & Smart: AF order exists

1951, Shull, Strauser & Wollan: FM order in (111) planes, noncollinear structure not excluded

1988, Shaked, Faber & Hitterman: collinear, spins oriented in (111) plane

2006, Goodwin & al.: oriented in <11-2> direction, slight out-of-plane component
Magnetic structure of MnO

nn: 6 ↑↑, 6 ↑↓  nnn: 6 ↑↑

C.G. Shull, W.A. Strauser & E.O. Wollan, Phys.Rev. 83 (1951) 333
MnO, a "simple" antiferromagnet

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Possible collinear magnetic structures on the simple cubic lattice

E.O. Wollan and W.C. Koehler, Phys.Rev. 100 (1955) 345
Magnetic structures of the rare earths

а  ferromagnet
б  spiral
в  conical ferromagnet
г  conical antiferromagnet
The ordered state of chromium

\[ a_{\text{magn}} = \frac{2\pi}{\delta} \]

E. Fawcett, Rev.Mod.Phys. 60 (1988) 209
The ordered state of chromium incommensurate

E. Fawcett, Rev.Mod.Phys. 60 (1988) 209
Frustration

Noncollinear, coplanar structure in CsNiCl$_3$

Water ice and spin ice

$\text{Dy}_2\text{Ti}_2\text{O}_7$, Pyrochlore structure

Heat capacity and entropy

Remanent entropy in water ice:

\[(R/2)\ln(3/2)\]

Pauling 1935

Predicted ground state

The spinel structure