2D magnetism and applications
Graphene makes experiments on phenomena in quantum physics possible.

- Opened the door to the creation of new materials and innovative electronics.
- Graphene transistors are predicted to be substantially faster than today's silicon transistors and result in more efficient computers.
- Practically transparent and a good conductor, graphene is suitable for producing transparent touch screens, light panels, even solar cells...
- When mixed into plastics, graphene can turn them into conductors of electricity while making them more heat resistant and mechanically robust: new super strong materials, which are also thin, elastic and lightweight.
- In the future, satellites, airplanes, and cars could be manufactured out of the new composite materials.
Until recently, there was no monolayer (semiconductor or insulator) with intrinsic magnetism. Monolayer metals with intrinsic magnetism indeed exist, but magnetic properties depend on substrate properties and interface quality. Isolated 2D magnets did NOT exist.
And now…

**Nature**

**Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals**

Cheng Gong, Lin Li, Zhenglu Li, Huiven Ji, Alex Stern, Yang Xia, Ting Cao, Wei Bao, Chenhuo Wang, Yuan Wang, Z. Q. Qiu, R. J. Cava, Steven G. Louie, Jing Xia & Xiang Zhang.

*Nature* **546**, 265-269 (2017) | Cite this article

**Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit**


**Nature Reviews Physics**

**Probing and controlling magnetic states in 2D layered magnetic materials**

Kin Fai Mak, Jie Shan & Daniel C. Ralph.

*Nature Reviews Physics* **1**, 646-661 (2019) | Cite this article
It emerged a large class of layered magnetic materials with unique magnetic properties, which provides an ideal platform to study magnetism and spintronics device concepts in the 2D limit.

Since these materials are atomically thin, their magnetic states can be effectively controlled or switched by external perturbations other than magnetic fields, such as electric fields, free carrier doping and strain.

New materials concepts, such as magnetizing 2D semiconductors by magnetic proximity coupling, and new devices, such as spin tunnel field-effect transistors, are rapidly emerging.

Although rapid progress has already been made, there are many opportunities and challenges remaining in this young field!
2D magnetism is currently an active topic at IFW. If you want to know more about how to work on it, search for these groups:

**Magnetic properties**
We investigate magnetic and electronic properties using thermodynamic methods, high field ESR and NMR spectroscopies.
To the research team

**Synthesis and crystal growth**
We are dedicated to the synthesis, crystal growth and characterization of materials with specific properties.
To the research team
Mermin-Wagner Theorem

In one and two dimensions, continuous symmetries cannot be spontaneously broken at finite temperature in systems with sufficiently short-range interactions.

At any non-zero temperature, a one- or two-dimensional isotropic spin-$S$ Heisenberg model with finite-range exchange interaction can be neither ferromagnetic nor antiferromagnetic.

The physics behind this theorem is based on the idea that the excitation of spin-waves can destroy the magnetic order.

\[ M(T) = M(T = 0) - \Delta M(T) \]

\[ \Delta M(T) \sim \int_{0}^{\infty} N(E) \left[ 1/(e^{E/k_BT} - 1) \right] dE \]

- Reduciton due to thermally excited spin-waves
- Probability for the thermal occupation
- Density of states of the excitations
- Depends on the dimensionality of the system!

Adapted from Magnetism in two dimensions and Mermin-Wagner theorem, Frank Schreiber, Uni Tuebingen
General case: excitations with a dispersion $E \sim k^n$ and a volume element in $d$-dimensional $k$ space $\sim k^{d-1} dk$.

$N(E) \sim E^{(d-n)/n} = constant$

For $n = 2$ (dispersion of spin-waves in FM (with Heisenberg-Hamiltonian) and $d = 2$ (two dimensions)

$\Delta M(T)$ diverges for finite $T$, which implies the breakdown of magnetic order, i.e. $M(T) = 0$ for $T > 0$.

The reason for the absence of magnetic order under the above assumptions is thus that at finite temperatures spin-waves are infinitely easy to excite, which destroys magnetic order.

However, be careful!

- assumption of "isotropic interactions": magnetic order could be stabilized by anisotropy.
- assumption of "short-range interactions": magnetic order may be stabilized with longer-range interactions.
- assumption of dimension $d = 2$ (or smaller): a slightly higher $d + \varepsilon$ dimension stabilizes the magnetic order.

Adapted from Magnetism in two dimensions and Mermin-Wagner theorem, Frank Schreiber, Uni Tuebingen
It has been recently shown that even a small uniaxial magnetic anisotropy can open up a large magnon* excitation gap, which in turn lifts the restrictions imposed by the Mermin-Wagner theorem and results in finite Curie temperatures below which a 2D magnet can practically survive.

Exchange interaction between spins can be direct, indirect mediated by conduction electrons or indirect mediated by intermediate anions such as O\(^-\). Magnetic anisotropy has sources such as magnetocrystalline, shape or stress anisotropy.

In a 2D isotropic Heisenberg ferromagnet, there will be massive magnon excitations at nonzero temperature, resulting in the collapse of magnetic ordering. However the presence of uniaxial magnetic anisotropy leads to a finite Curie temperature.

In 3D systems, uniaxial magnetic anisotropy is not a requirement for the appearance of finite-temperature long-range magnetic order.

* Quanta of spin-wave
The first two reported 2D magnetic atomic crystals are chromium compounds: CrI$_3$ and Cr$_2$Ge$_2$Te$_6$. 

A monolayer is an intrinsic ferromagnet, whereas atomically thin CrI$_3$ is a layered antiferromagnet: intralayer coupling is ferromagnetic while interlayer coupling is antiferromagnetic!

CrI$_3$ could become a key component for van der Waals structures with spintronic functionalities, topological properties...etc.!

The first experimental discovery of intrinsic long-range ferromagnetic order. Additionally, an unprecedented control of transition temperature was realized via small fields.
Fe-based van der Waals magnets: Fe$_3$GeTe$_2$

- Has emerged as an alternative for CrXTe$_3$, because of its higher Curie temperature (~230 K) and higher stability against oxidation.

The metallic character of 2D-VX$_2$ (X = S, Se, Te) stems from its odd 3d$^1$ electronic configuration, which also invokes exotic quantum phenomena, such as charge density wave (CDW) and magnetism.
Spintronics context

2D Spintronics
- Charge spins
- 2D materials

Challenges & Opportunities
- Scalability
- Ambient stability
- Curie temperatures
- Interface-induced magnetic phenomena: half-metallicity at Co/MoS₂ interface, giant magnetoresistance in vertical Fe/MoS₂/Fe junction, PMA at CoFeB/MoSe₂ interface, interface magnetic proximity, spin-orbit torque, spin pumping, multiferroicity, 2D spin-liquids, skyrmions...

2D-vdW Magnets
- Extrinsic magnetism: defect engineering, surface functionalization, doping
- Intrinsic magnetism: CrX₃ (X = Cl, Br and I), CrGeTe₃, Fe₃GeTe₂, MnX₂ (X = S, Se), VX₂ (X = S, Se, Te), and 2D oxides, halides, nitrides, carbides...
- Devices: vdW-MTJs...

Advances in Growth & Characterization Techniques
- Specialized growth techniques: gas-assisted MBE, plasma-assisted MBE...
- Nanoscale magnetic characterization tools: scanning single-spin magnetometry...
Graphite/\text{CrI}_3/graphite sandwich structure that possesses a large tunneling magnetoresistance. The \text{CrI}_3 bilayer functions as a spin-filter.

Two thin \text{Fe}_3\text{GeTe}_2 crystals of different shape and thickness (L1 and L2, respectively \sim 7 and 20 nm thick), are separated by an atomically thin hBN layer. Structures are encapsulated with a thicker hBN layer (typically 30-50 nm thick).
Devices: Heterostructures combined with other materials

Compared to the approach to interfacing 2D materials with 3D magnets, a van der Waals heterostructure has several advantages:

✓ lattice mismatch is not an issue, thus minimizing chemical modification and interfacial damage, which is desirable for engineering a clean interface for optimal interactions.
✓ Single crystals use facilitates the ability to engineer and study magnetic multilayer van der Waals stacks with unique spin textures.
✓ The flexibility of the layer stacking process also facilitates the creation of van der Waals heterostructures between layered ferromagnets and a diverse set of other 2D materials.

Graphite/CrI$_3$/graphite sandwich structure that possesses a large tunneling magnetoresistance. The CrI$_3$ bilayer functions as a spin-filter.


Nano Lett. 2018, 18, 3823-3828
And what about antiferromagnets?

FM materials have been widely analyzed, but research on AFM materials did not progress with the same speed. The main reason is that it is very difficult to measure in detail the magnetic properties of such a thin AFM material.

Exciting possibilities for AFM materials would be making field-effect transistors, tunneling devices, and photodetectors.
Characterization tools capable of probing 2D magnetism in vdW crystals need equal attention as the growth techniques. The classic macroscopic analysis tools cannot be applied. Local probes with a spatially-resolved capability are clearly advantageous. Which ones would be suitable?