1. History of 2D materials

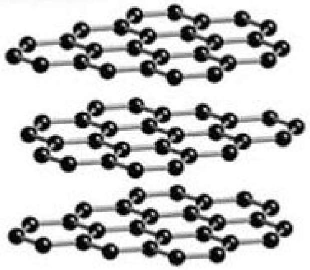
Rise of Graphene

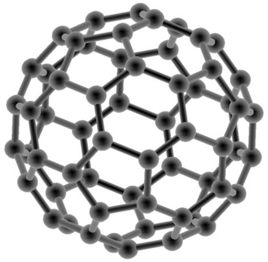
3D

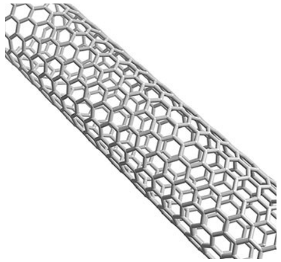
0D

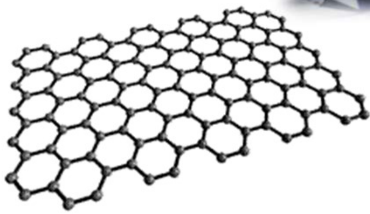
1D

2D









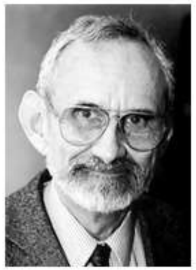
Borrowdale — *1564*

Curl, Kroto, Smalley — *1985*

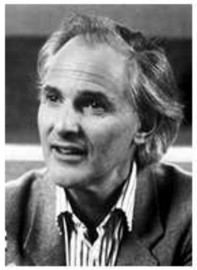
MWCNT
SWCNT — *1993*

Geim, Novoselov — *2004*

The Nobel Prize in Chemistry 1996



Robert F. Curl Jr.
Prize share: 1/3



Sir Harold W. Kroto
Prize share: 1/3

Richard E. Smalley
Prize share: 1/3

The Nobel Prize in Chemistry 1996 was awarded jointly to Robert F. Curl Jr., Sir Harold W. Kroto and Richard E. Smalley *"for their discovery of fullerenes".*

The Nobel Prize in Physics 2010

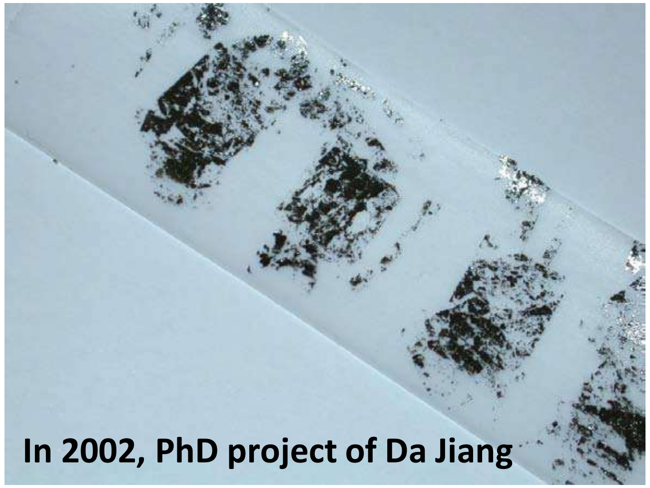
Photo: U. Montan
Andre Geim
Prize share: 1/2

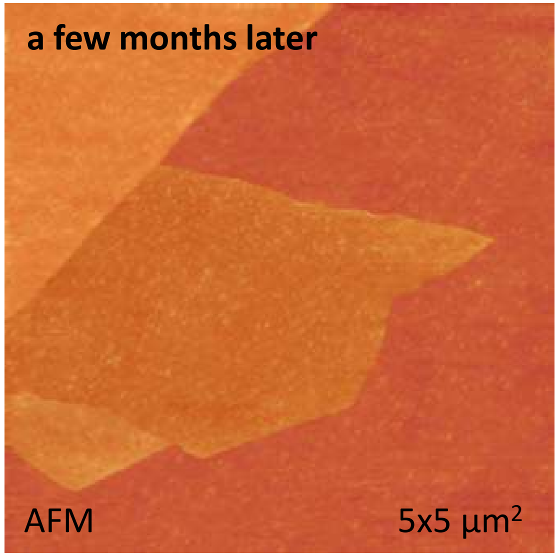
Photo: U. Montan
Konstantin Novoselov
Prize share: 1/2

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

History of Graphene

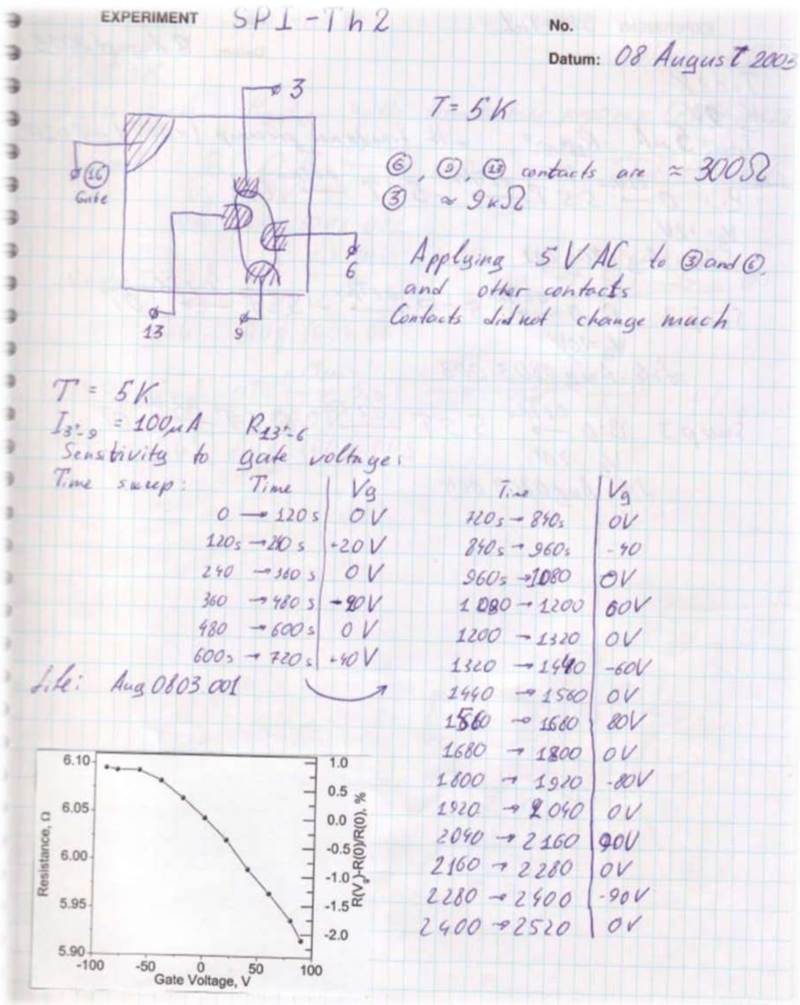
By Manchester group





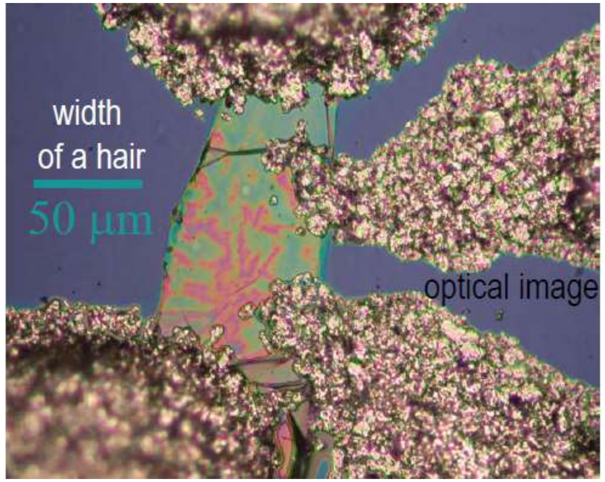
History of Graphene

Novoselov's research notebook



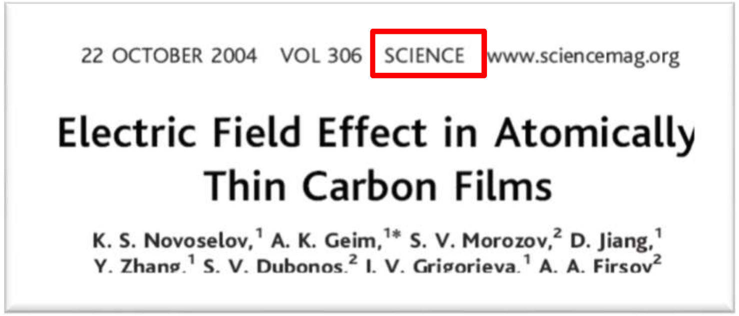
resistance changed by as much as ~3%: bad "metallic transistor"

World-first hand-made graphene device



And after a lot of hard work ...

down to a single layer; devices down to ~3 layers
on-off ratios ~30 at room T and >100 at low T



22 OCTOBER 2004 VOL 306 SCIENCE www.sciencemag.org

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

twice rejected by Nature!!

History of Graphene

massless and massive Dirac fermions

two new types of the quantum Hall effect

metallic in the limit of no charge carriers

universal optical conductivity defined by the fine structure constant

Klein tunneling

tunable-gap semiconductor

giant pseudo-magnetic fields by elastic strain

new type of chemistry: graphane & fluorographene

possibility of carving devices on a true nm scale

sensors capable of detecting individual gas molecules

superconductivity in magic-angle graphene superlattice

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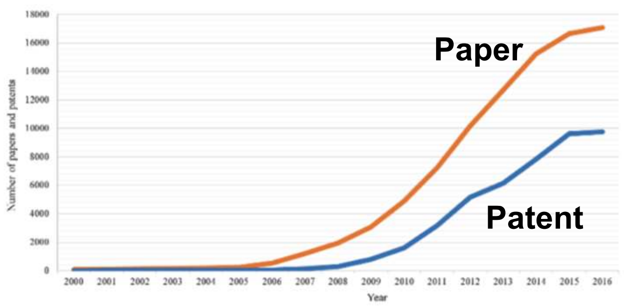
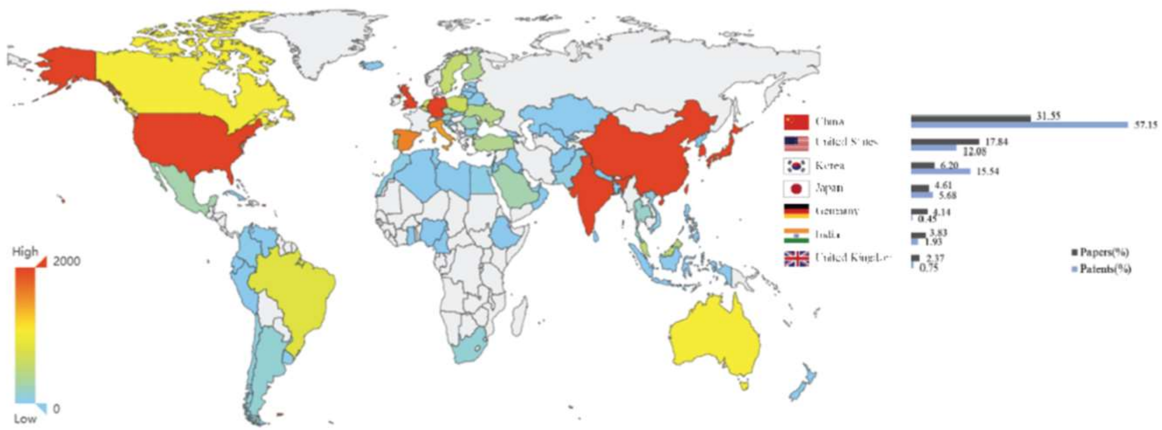
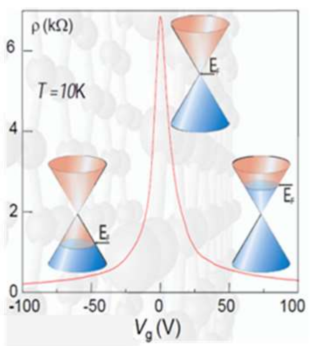
many more beautiful observations by various researchers for a decade…

Graphene research in world



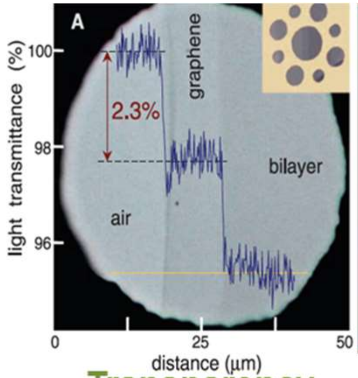


Fame of Graphene

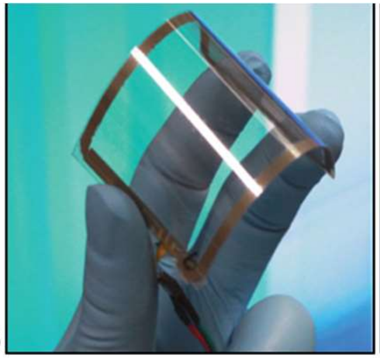


High Conductivity

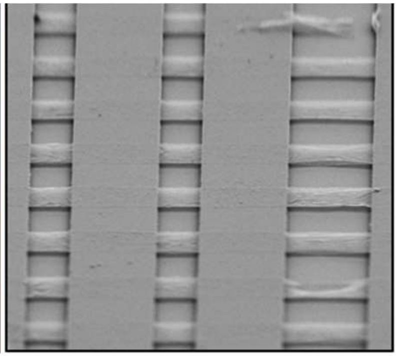
High strength



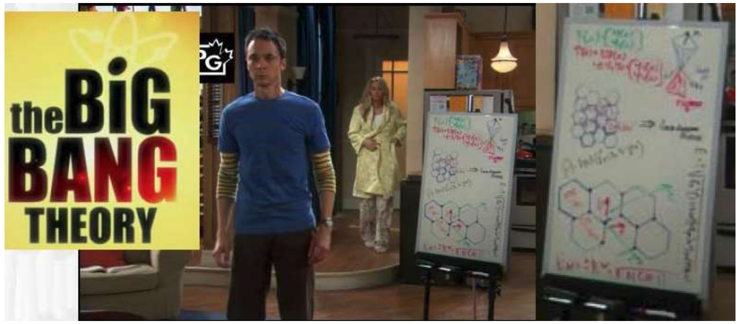
Transparency



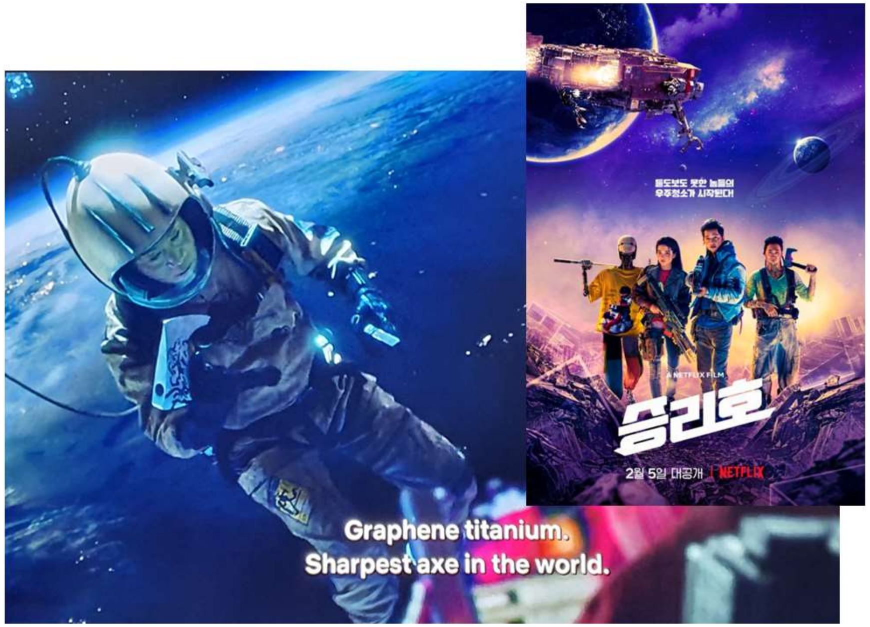
Flexibility



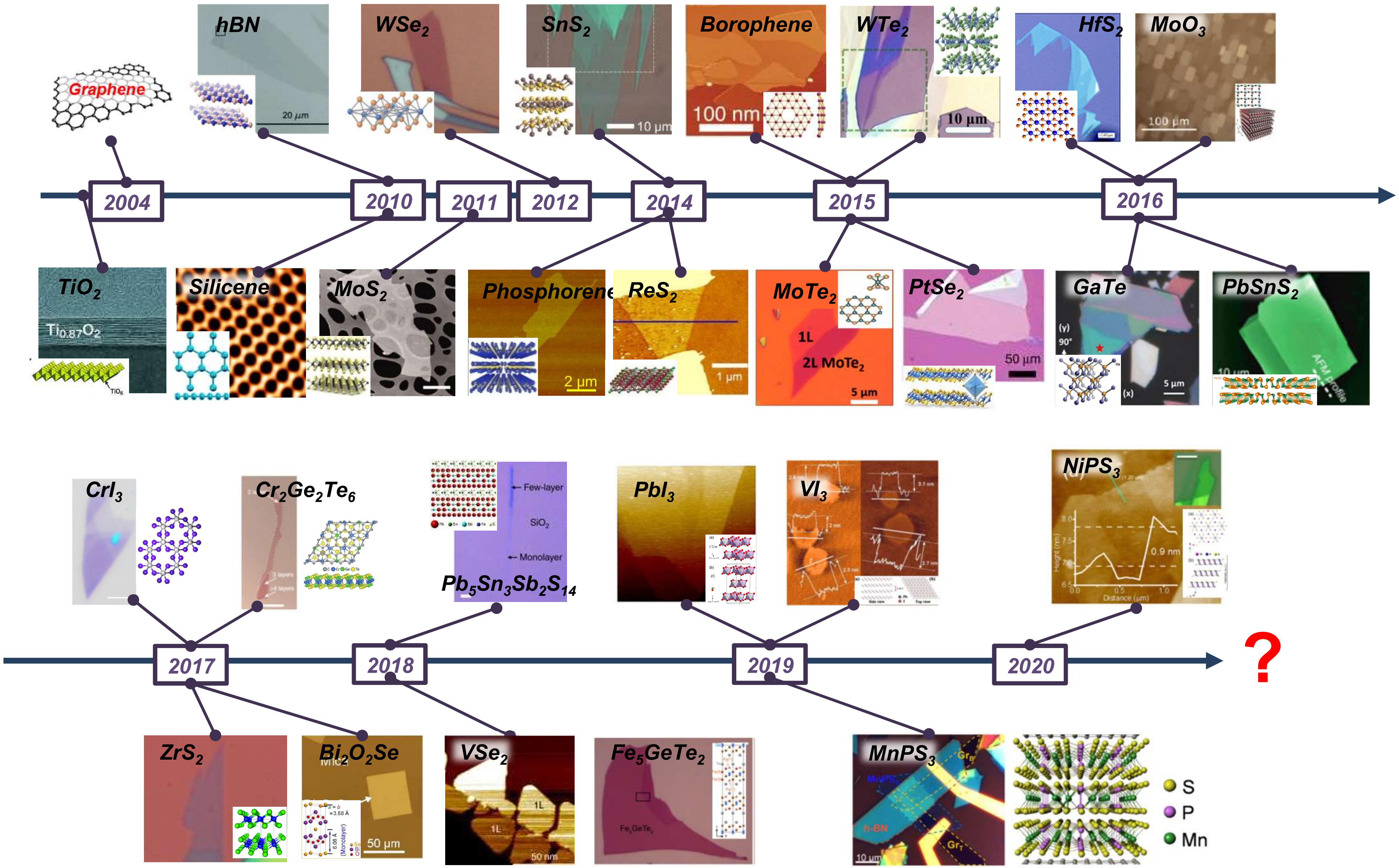
Easy patterning



Tallahassee, Florida, USA



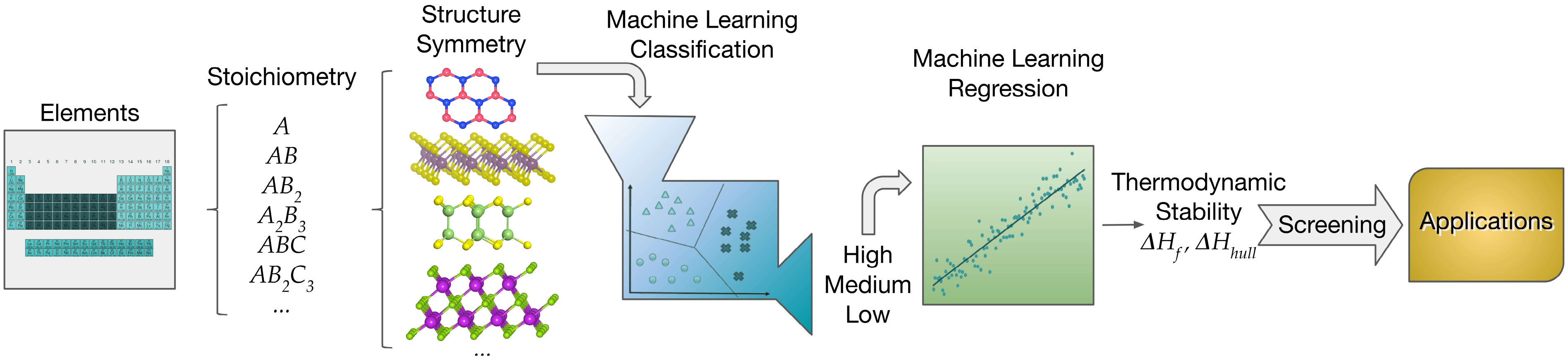
Continuous Finding of 2D Materials



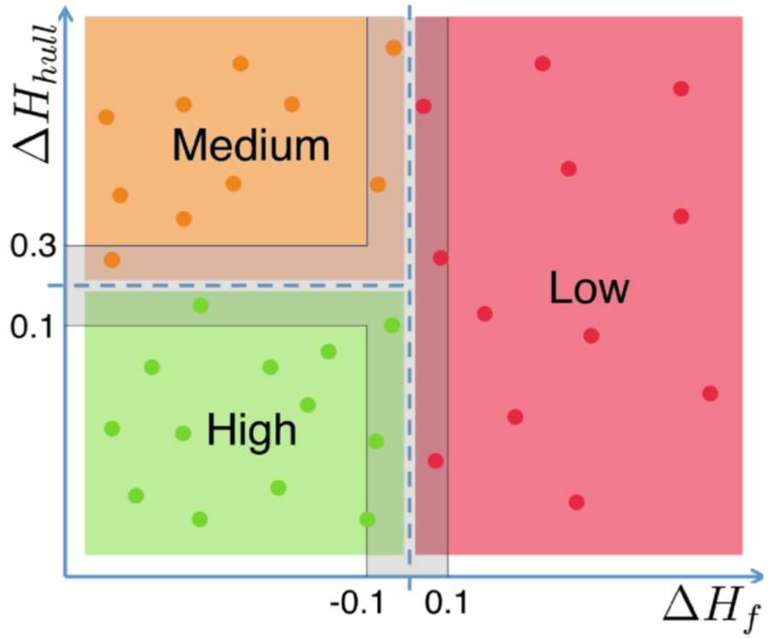
Continuous Finding of 2D Materials

Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2	Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on		
			Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on		
2D oxides	Micas, BSCCO	MoO_3, WO_3	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on	
	Layered Cu oxides	TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on		Others	

Finding 2D materials through Machine learning



Thermodynamic stability



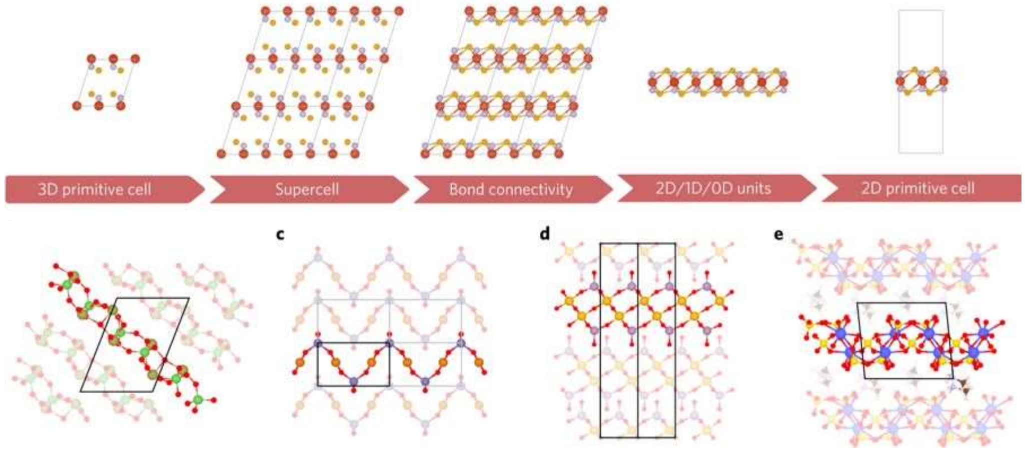
Experiments

Synthesis of monolayer & few layer

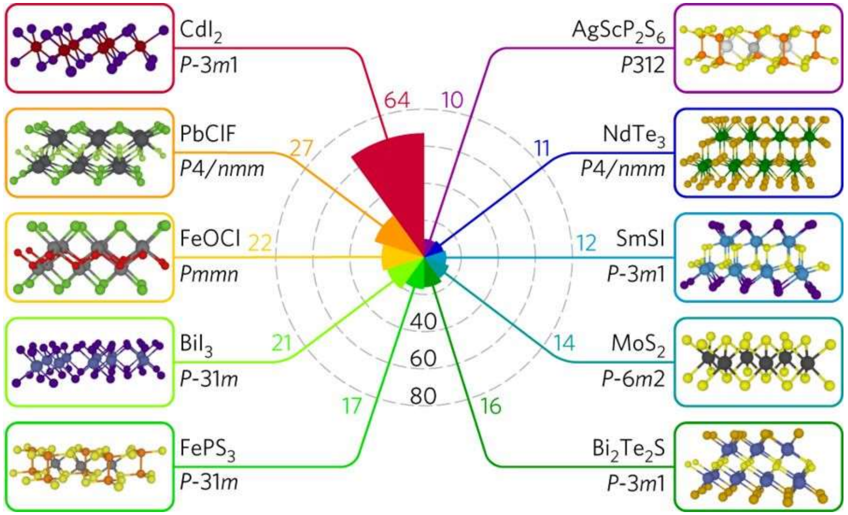
Synthesis of bulk crystal & Exfoliation

ACS Appl. Mater. Interfaces (2019)

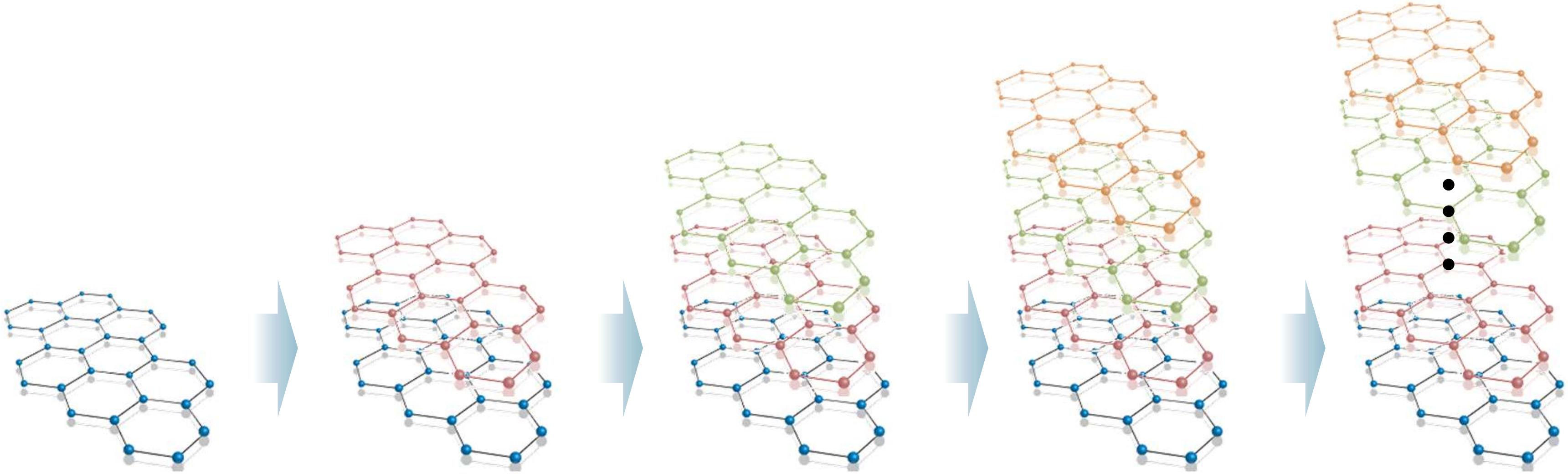
Infinite Number of Exfoliable 2D Materials



Nature Nanotechnol. *13, 246–252 (2018)*



a set of 1,036 easily exfoliable 2D materials



1,036

$1{,}036^{2}$
= 1,073,296

$1{,}036^{3}$
= 1,111,934,656

$1{,}036^{4}$
= 1,151,964,303,616
= 10^{12}

$1{,}036^{1{,}036}$
~ infinite

Contents of class

Properties	Metal (Graphene), Semiconductor (TMDs), Insulator (hBN), Magnet, Topological insulator
Growth	Scalability, Quality (Crystallinity & Uniformity), Transfer & Contamination, Heterostructure
Heterostructure	Advantage, Stacking technique, interface between vdW layers, Emerging applications
Defects	Types (sp^3, vacancy, hole, grain boundary) Healing, Doping, Defect engineering
Analytical tools	AFM, Raman & Photoluminescence, TEM, I-V measurement, Standardization
Applications	Electronics, Photonics, Telecommunications, Spintronics, Energy harvesting & Storage, Composition