

The last piece of the puzzle?

Graphene

Adrian Nixon

15th June 2019



Adrian Nixon: Who is he?

<https://www.linkedin.com/in/adriannixon/>

A qualified industrial chemist,
member of the Royal Society of Chemistry



Over 20 years experience in industry;
Technical Service and R&D, Author of several patents

Senior editor at InvestorIntel
Focused on graphene

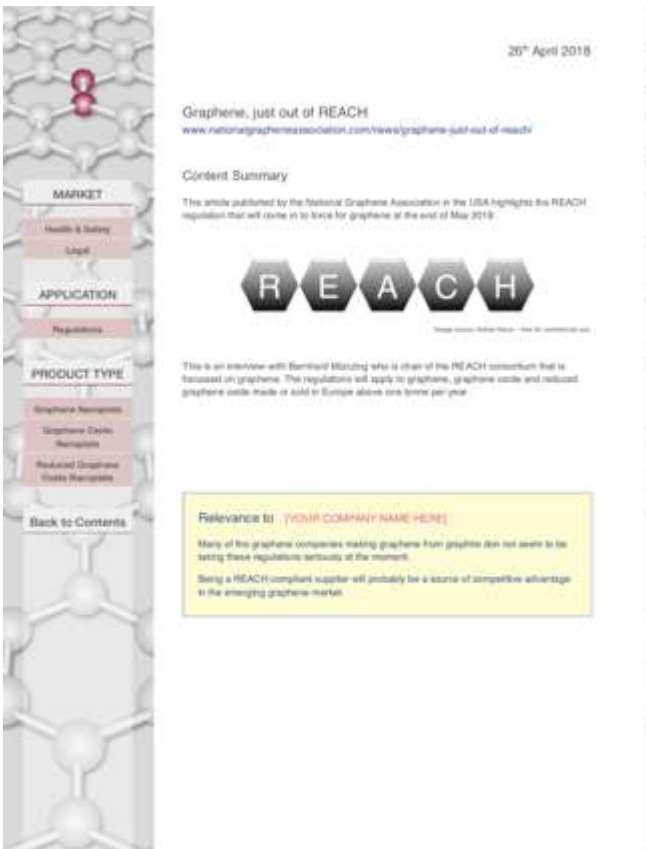


Editor of the Nixene Journal
Focused on graphene and 2D

NixeneJournal

Advisory Board member of the
National Graphene Association in the USA



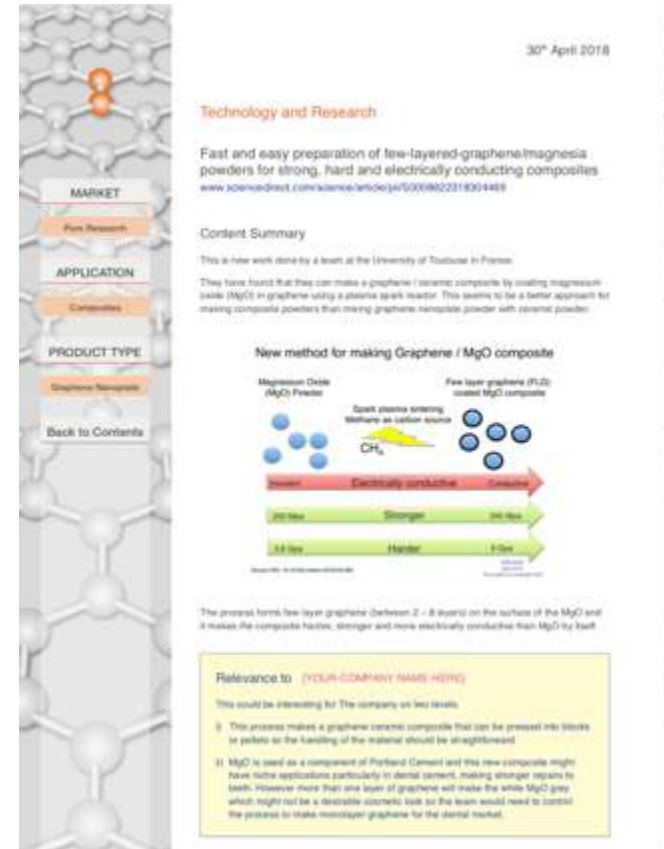


Selling in UK
Since autumn 2017

Being launched
in Europe

Also launched in
USA
October 2018

Sample copy
available free at:
<https://www.nixor.co.uk/the-nixene-journal/>



Analysis of technology and business in the graphene and 2D world monthly report – one topic to each page.

Translates the jargon to plain English – addresses the ‘So What’
Creating clear information for decision makers

Briefing US Government and industry about
graphene and also the space elevator
at the American Graphene Summit 21-22 May 2019



On to the Space Elevator...

The feasibility explored by NASA...

The 21st Century



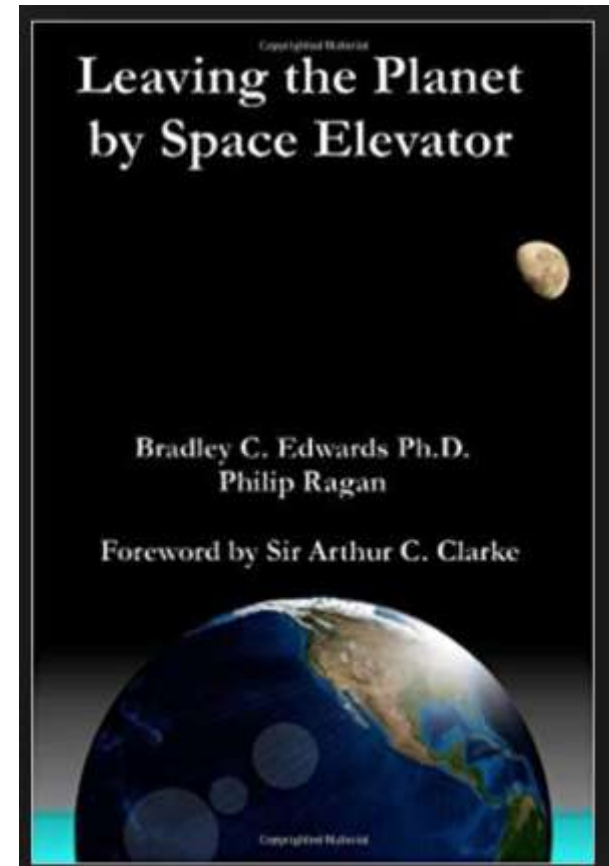
In 2000 NASA's Institute for Advanced Concepts NIAC

Commissioned Dr. Bradley C Edwards to examine the reality of the space elevator
He reported phase 1 in Oct 2000
Phase 2 in March 2003

Asked is this do-able with today's technology?

Answer, **Yes** – Apart from one thing...

https://en.wikipedia.org/wiki/Bradley_C._Edwards



Then the feasibility explored by the IAA...

The 21st Century

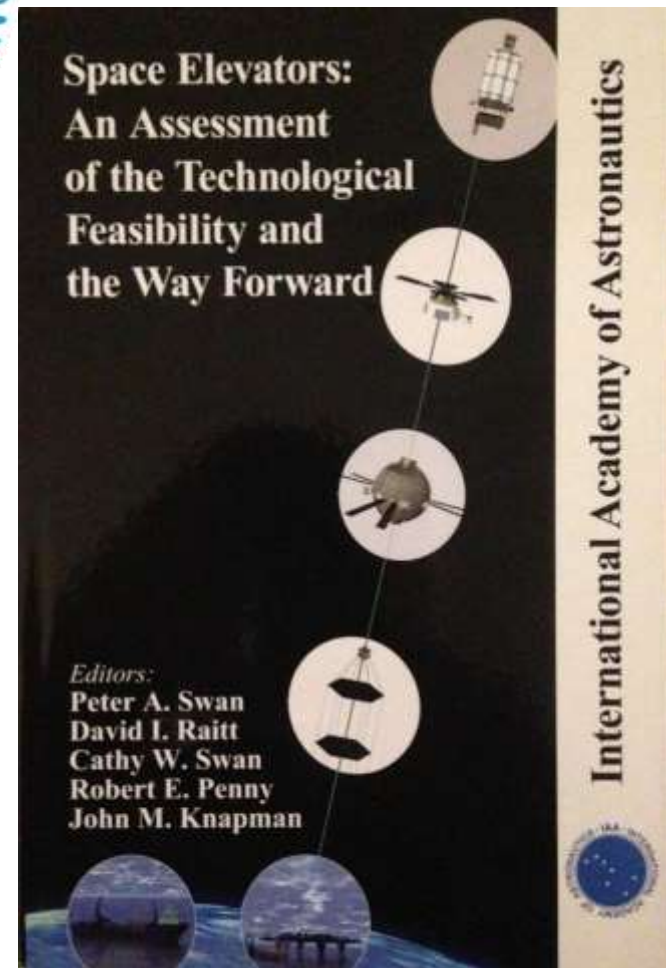
In 2013 The IAA

Looked at technical and commercial issues

Asked is this feasible to build, and how might we actually do this?

Answer, This can be done – Apart from one thing...

<https://www.amazon.co.uk/Space-Elevators-Assessment-Technological-Feasibility/dp/2917761318>



The Tether...

Dr Edwards' feasibility study ended and reported in 2003

A tether material needs to be incredibly strong and light

He recommended carbon nanotubes for the tether

However no one has been able to make them long enough

Graphene was isolated in 2004 and became public in 2010

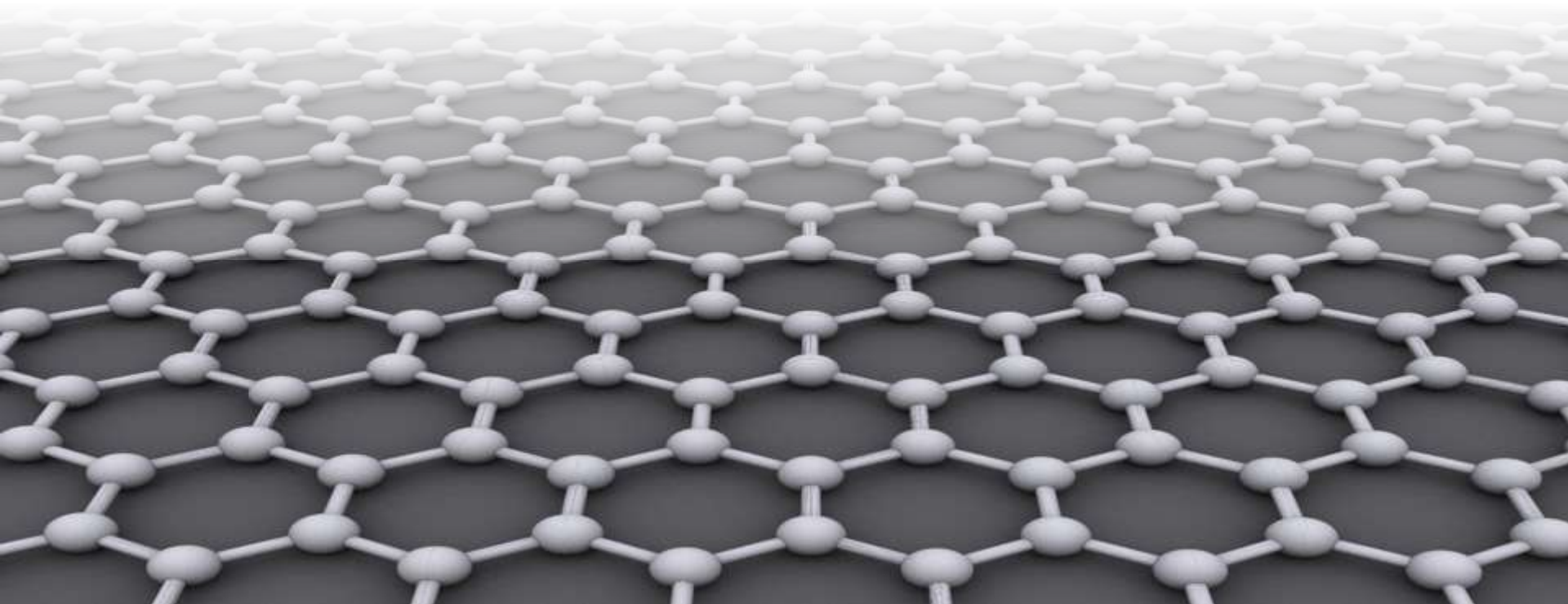
So, is graphene a suitable material to make a tether?

Graphene – What is it...

World's thinnest material, made of carbon

Think of a sheet of hexagons connected together rather like chicken wire and you'll get the idea

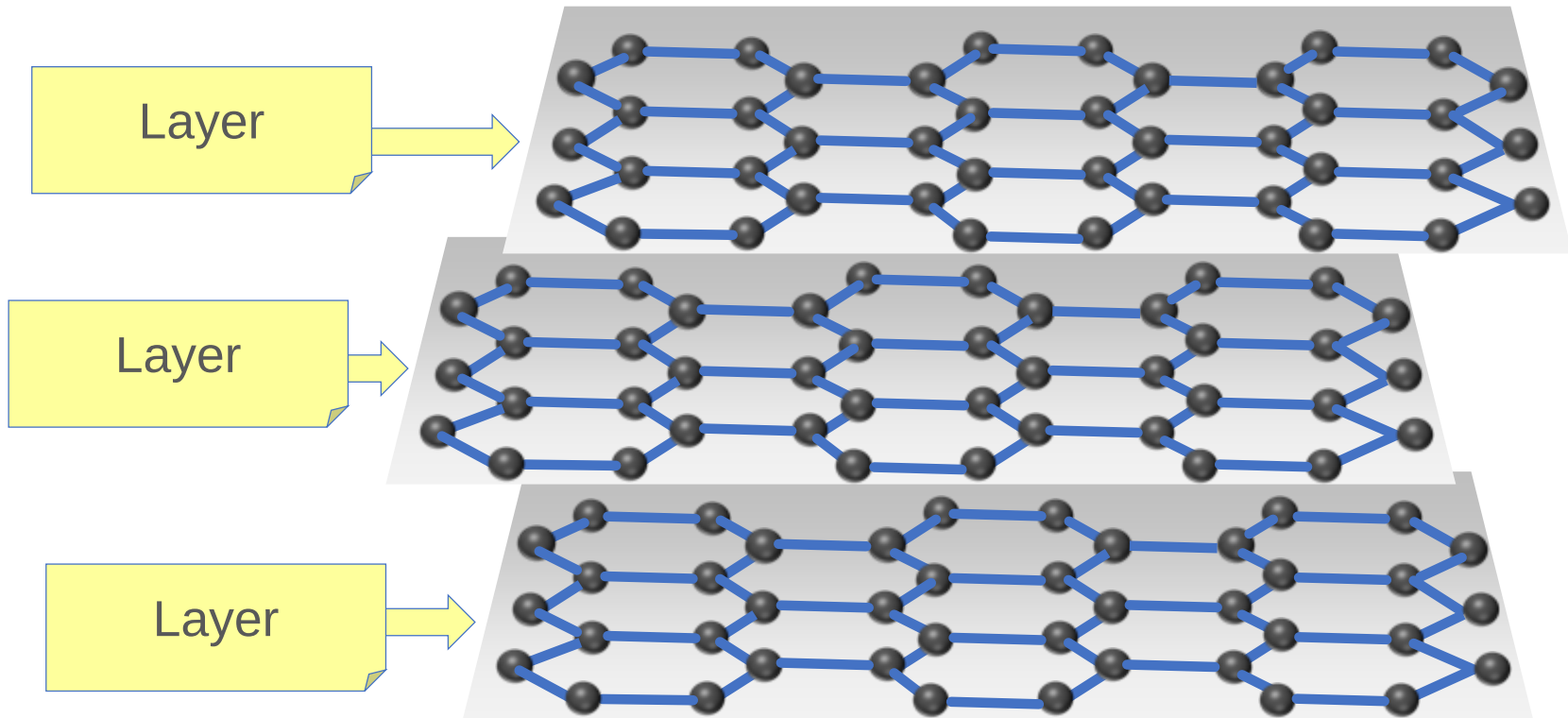
Graphene occurs naturally in graphite and it can be mined



Very pure graphite

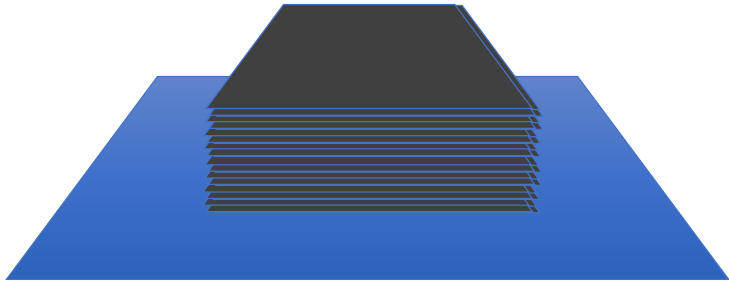


Graphene layers stack to form graphite

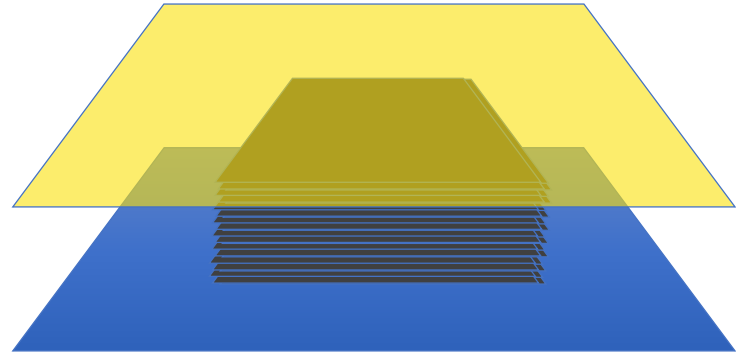


Three layers are shown here as an example highlighted in gray
The bonds within the layers are strong but are weak between layers

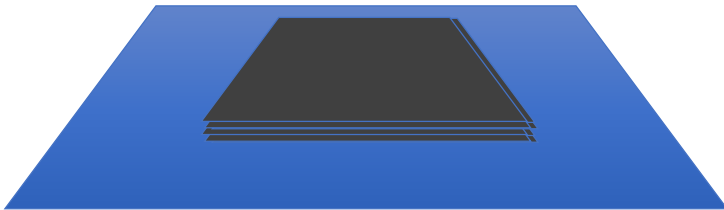
Graphene first made by hand from graphite by exfoliation with sticky tape



Graphite attached to a surface



Place adhesive tape on the graphite
And peel off taking some layers away



Repeat the peeling process



Finally one monolayer of graphene remains

Nobel Prize in Physics 2010: Graphene



2010

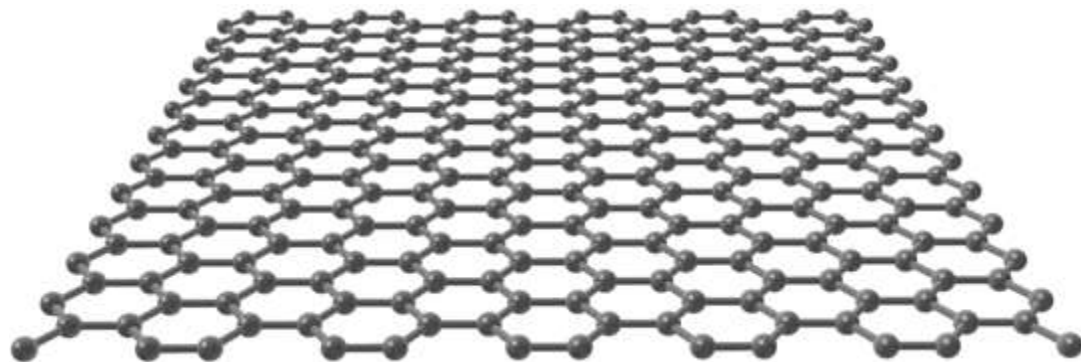
Andre Geim &
Konstantin Novoselov
Win Nobel Prize
For preparing and
characterizing
graphene



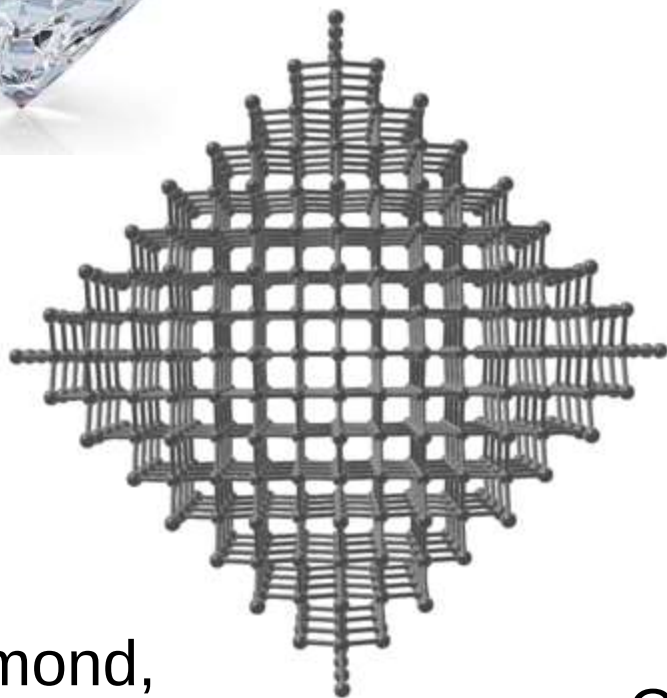
Graphite

2004,
Graphene
isolated as
world's first
2D material
using
sticky tape

The carbon family: Dimensions



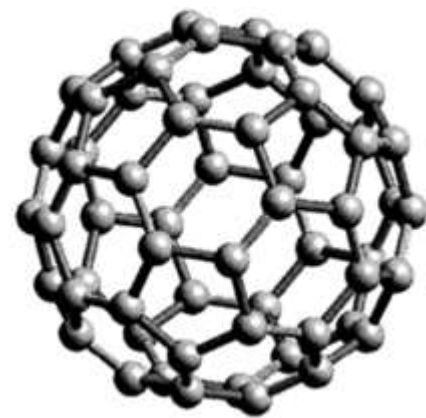
Graphene:
2D material



Diamond,
Amorphous Carbon:
3D material

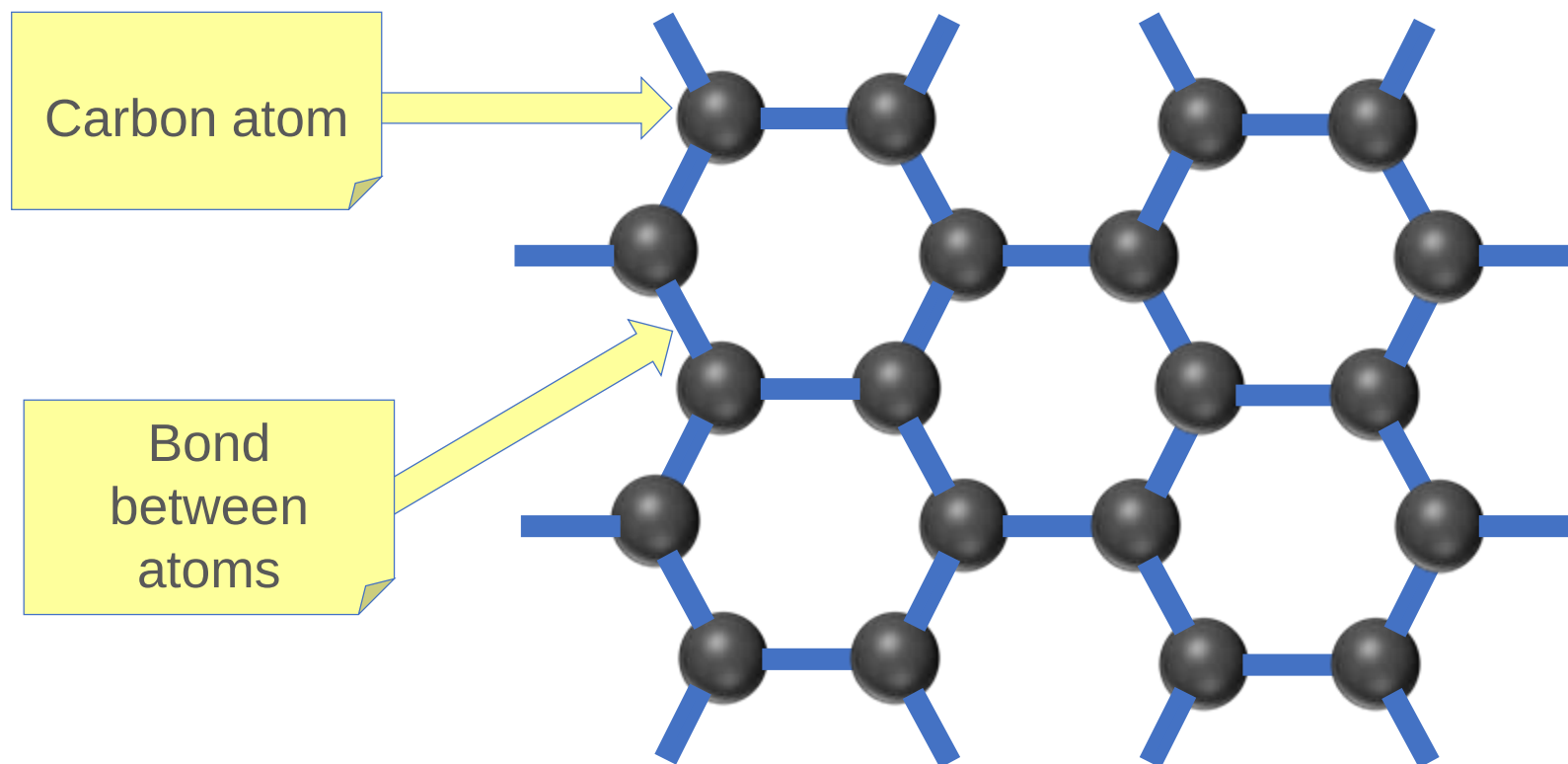


Carbon nanotubes:
1D material



Fullerenes:
0D material

Structure of graphene - the single 2D layer



Each carbon atom is bonded to the others in a flat hexagonal layer

Graphene – Why it is important...

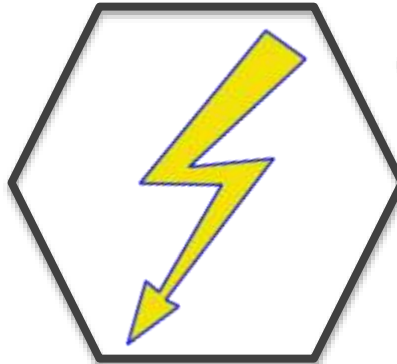
200 times
stronger
than steel



100 times
more tear
resistant
than steel



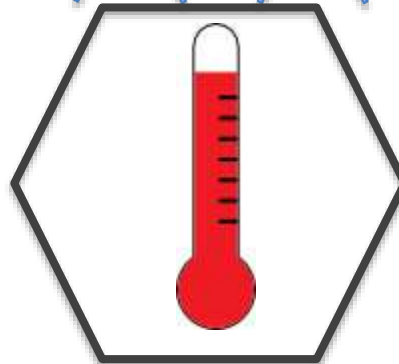
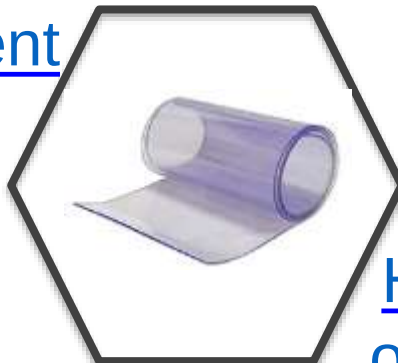
World's best
electrical
conductor



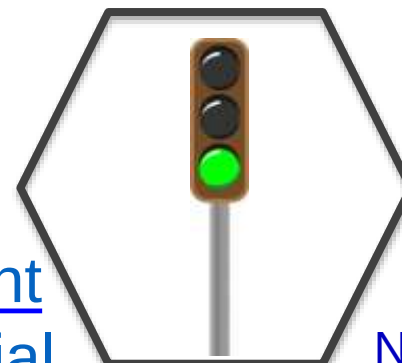
World's best
conductor
of heat



Flexible and
Transparent



Highest melting point
of any known material

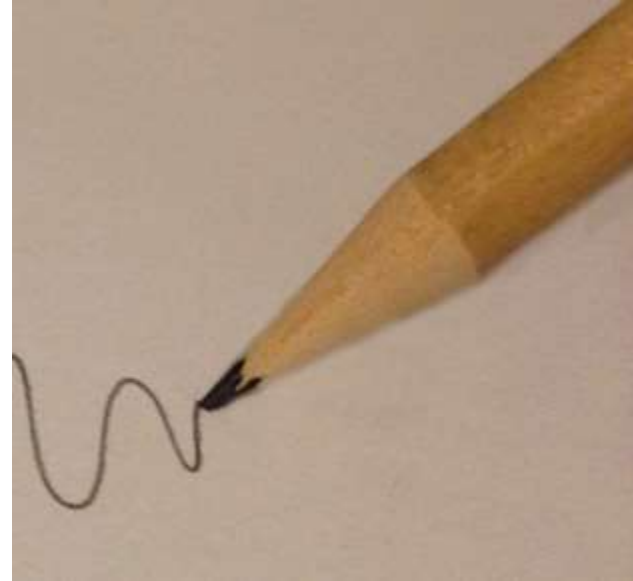


Very
Stable

Nixene Journal

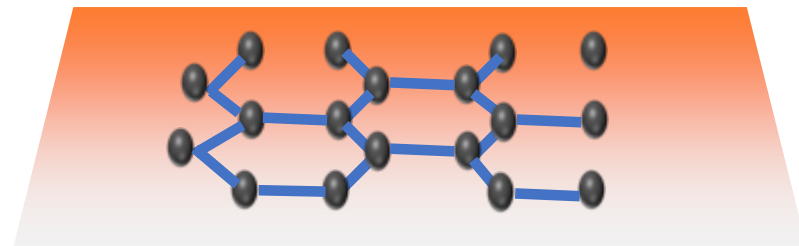
How is graphene made?

Top Down method from graphite
Current Commercial Quantities



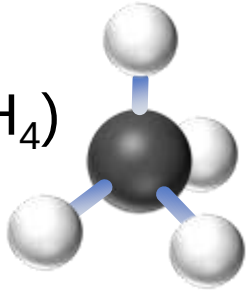
Bottom Up method – atom by atom
Chemical Vapour Deposition from Methane

- Some other methods include silicon carbide
- Still at laboratory scale

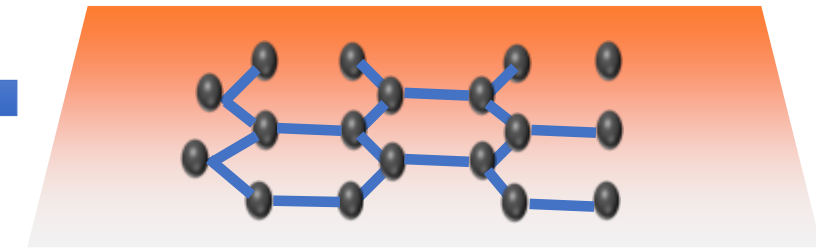
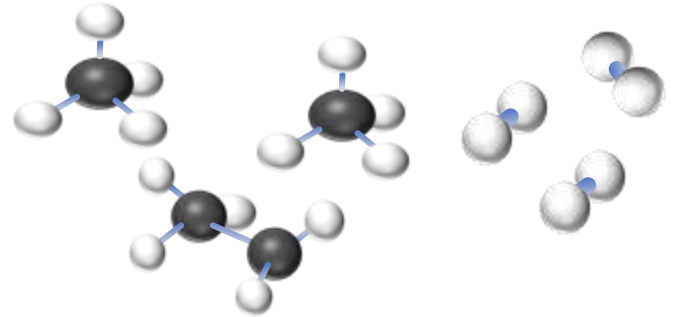


Making graphene from the 'bottom up' By Chemical Vapour Deposition

Pass heated
methane gas (CH_4)
Over a metal
(Copper) surface

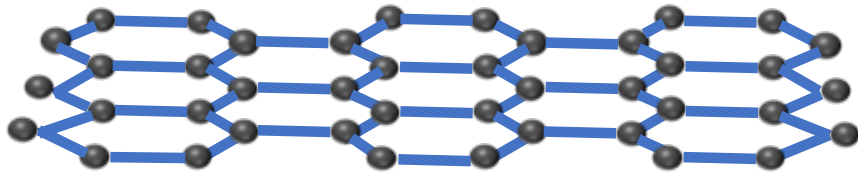


The copper helps
carbon and hydrogen
separate from the methane



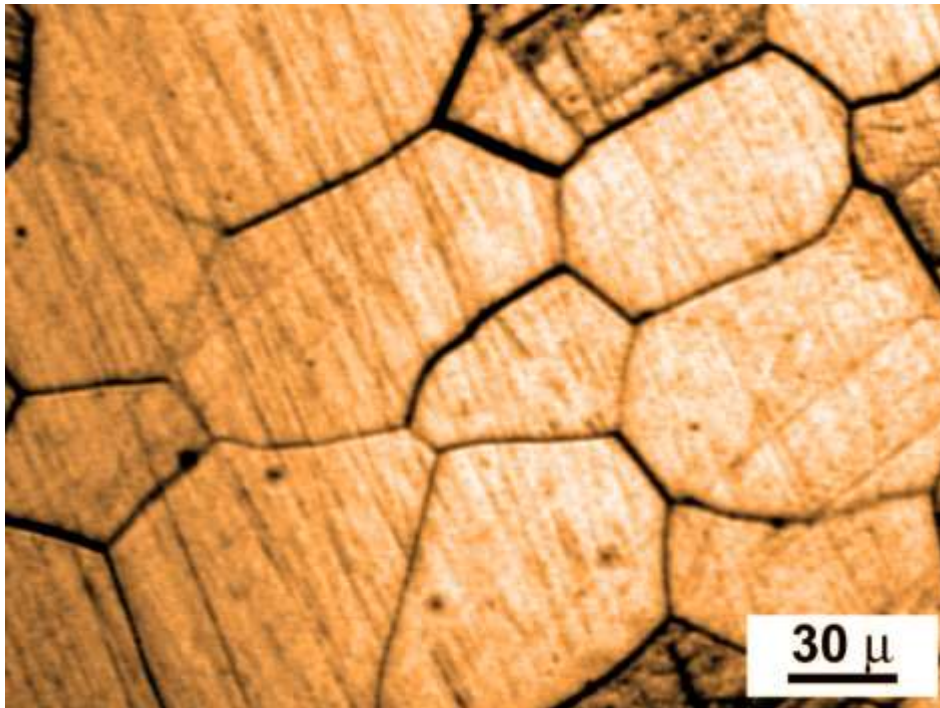
Carbon builds up on the copper
as a hexagonal graphene layer

Remove the copper to leave
the one atom thick graphene sheet



CVD production problems

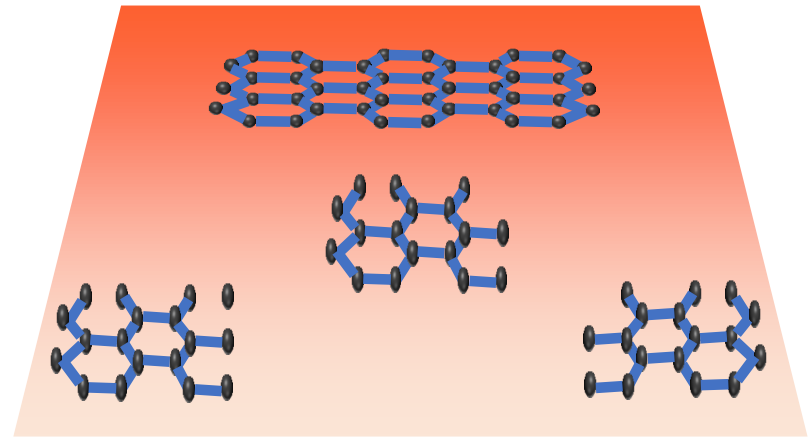
Metals like copper contain
crystal grain boundaries
That cannot be removed



Graphene picks up
these discontinuities

https://en.wikipedia.org/wiki/Grain_boundary

Snowflake deposition



Graphene starts to grow
At many places
Where these domains collide
Discontinuities are created

Graphene sheet: Space elevator requirements

Graphene nanoplates:

Graphene in separate tiny pieces from graphite

CVD Graphene:

Sheet graphene at cm^2 scale

Stuck on copper or other substrate

Contains many defects, not perfect sheet

Space Elevator Tether Quality:

Single crystal graphene

Perfect sheet – no defects

Hundred thousand km long 1000mm wide

Making space elevator tether quality graphene

CVD type of method most likely

Have to overcome production problems

A continuous process needed

Kilometres long single crystal graphene

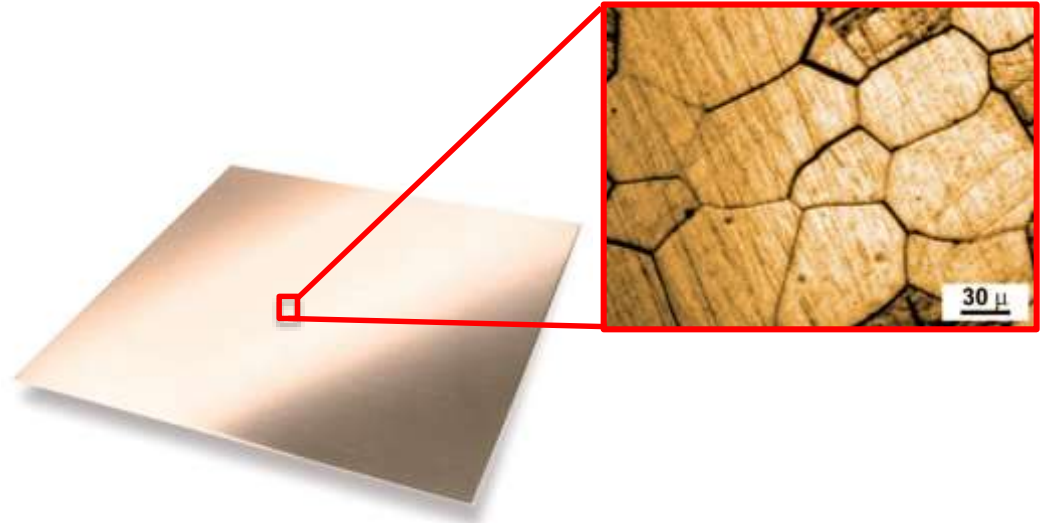
State of the art of graphene manufacturing



Graphene nanoplate

Black powders and liquids

Commercially available
as additives
for other materials



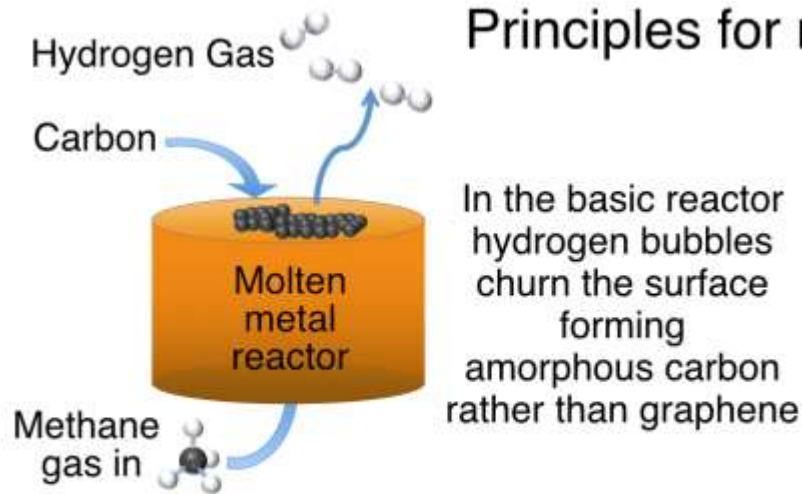
CVD Graphene

One atom thick

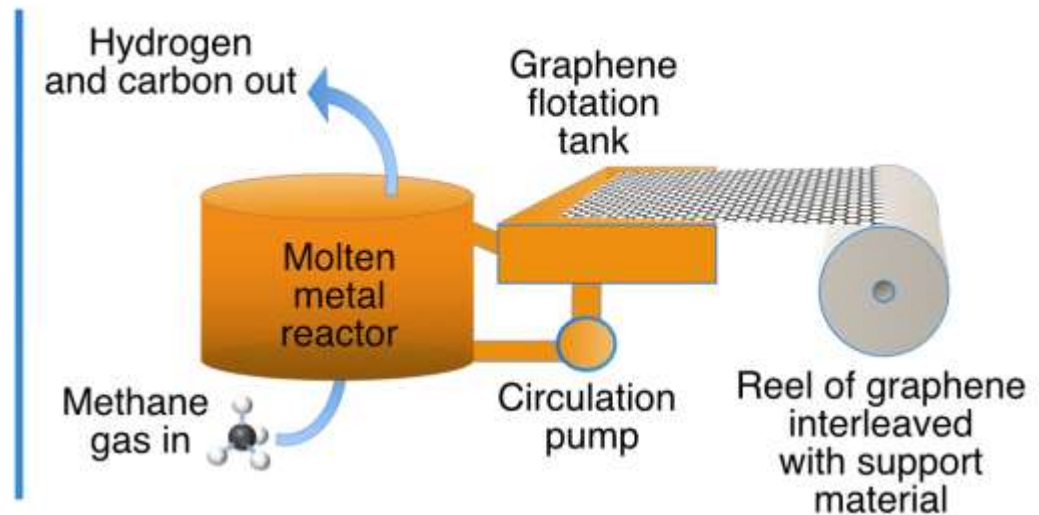
Imperfect layers of graphene
stuck on various surfaces

Graphene is not living up to its early promise

Overcoming CVD production problems: A continuous process

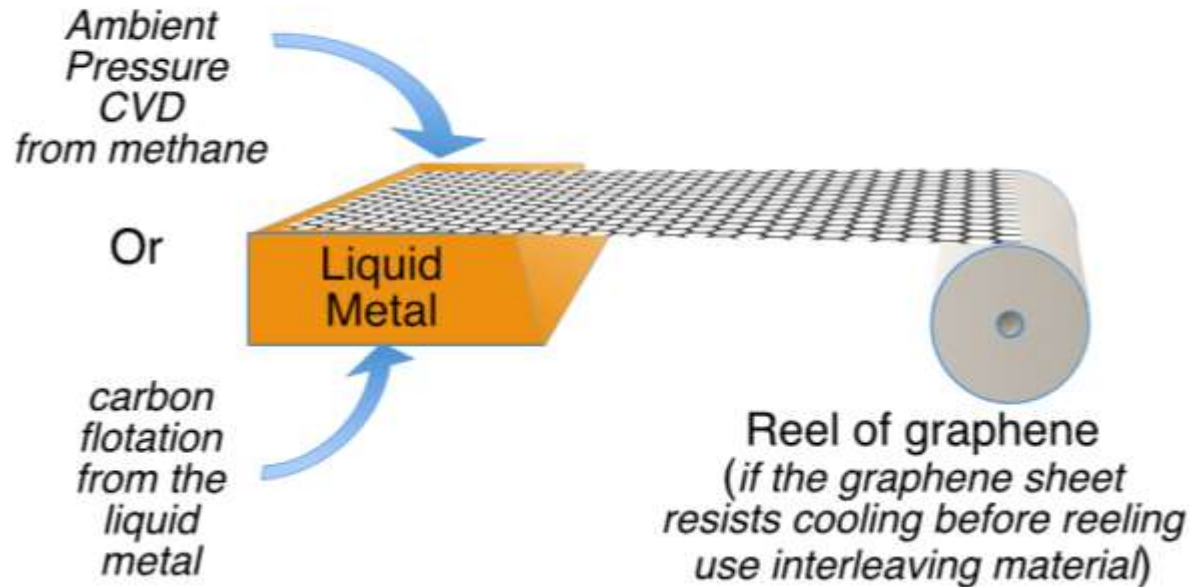


Principles for making sheet graphene



Graphene: A new continuous process

Principles for making continuous single crystal sheet graphene



I published the hypothesis to test it amongst the world's top graphene scientists. (While retaining key intellectual property)

This hypothesis has not been invalidated to date.

Products: Single crystal graphene

Crystal in this context means a repeating pattern forming something like cling film (one atom thick) rather than the everyday perception of a brittle solid



Single crystal graphene is the term for large scale sheets of defect free graphene. (a single molecule)

This image is of plastic film
Not graphene

Is single crystal graphene real?

Something happened in China in 2017...



Science Bulletin

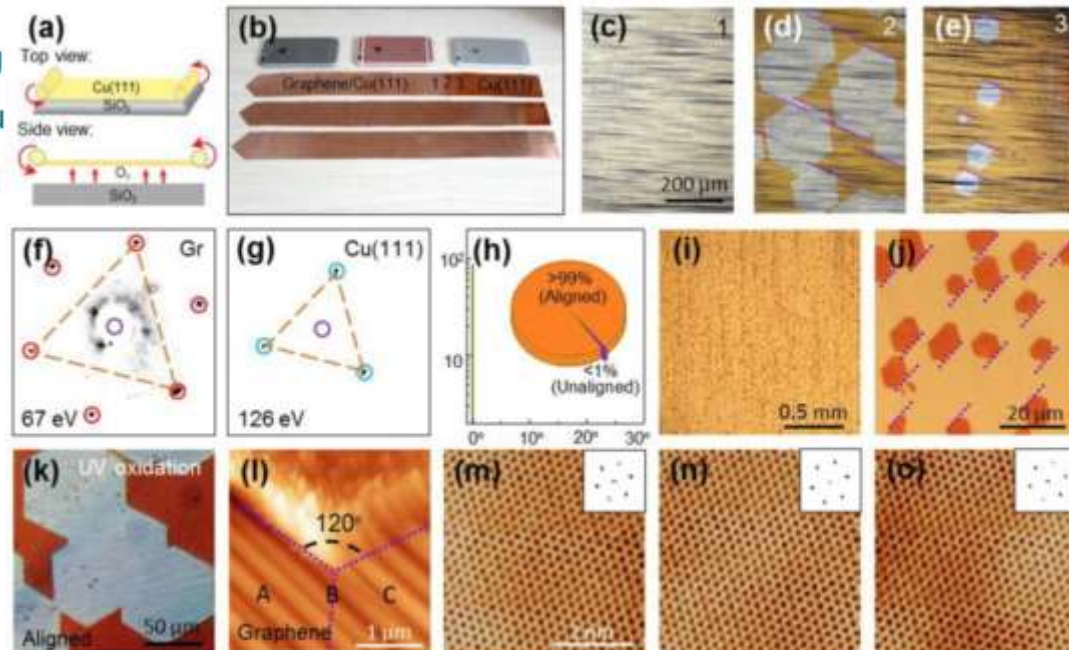
Volume 62, Issue 15, 15 August 2017, Pages 1074-1080



Article

Ultrafast epitaxial growth of metre-sized single-crystal graphene on industrial Cu foil

Xiaozhi Xu ^{a, b, 1}, Zhihong Zhang ^{a, b, 1}, Jichen Dong
Lin ^d, Rongkang Yin ^e, Mingqiang Li ^a, Jingyuan Zhou
Duan ^{d, e}, Peng Gao ^{a, d, g}, Ying Jiang ^{g, h}, Xiaosong
Kaihui Liu ^{a, d, g} ✉



<https://investorintel.com/sectors/technology/technology-intel/single-crystal-graphene-next-manufacturing-frontier/>

Single Crystal Graphene exists in the lab

The team at Peking University started by annealing a copper shape from the point to create a single crystal of metal with no grain boundaries



Then they arranged the growing conditions to form hexagon domains
These domains aligned and joined up rather than form discontinuities



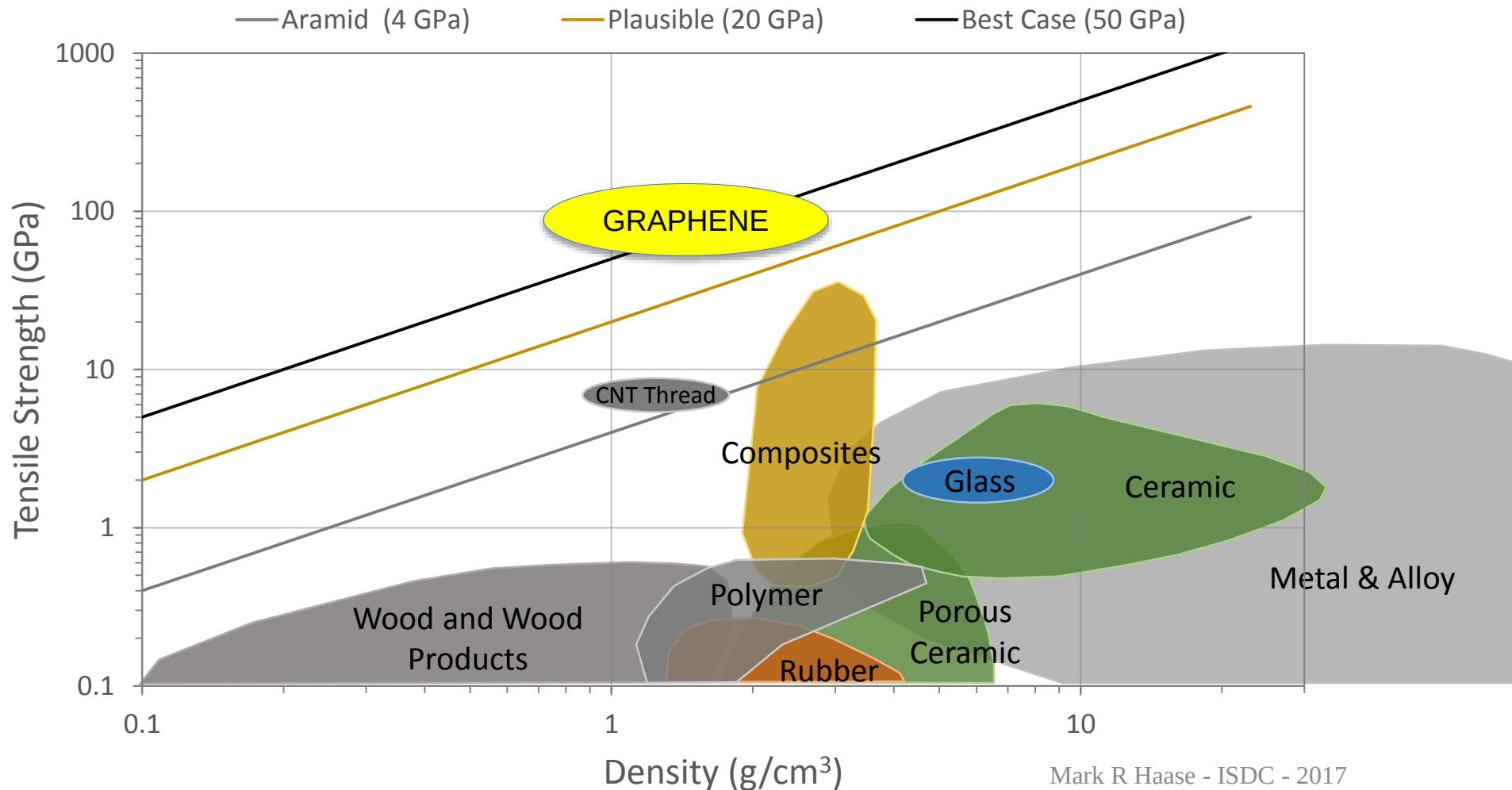
This produced a sheet of continuous graphene that contained 99% ultra highly orientated grains forming a single crystal 50mm x 500mm

Source: X. Xu et al. (2017) Ultrafast epitaxial growth of metre-sized single-crystal graphene on industrial Cu foil, Science Bulletin 62. 1074-1080

Tether candidate materials

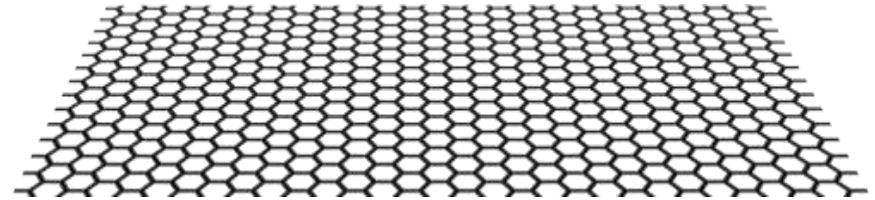
YES: Graphene is strong enough to be a candidate tether material

Ashby Plot - Tensile Strength vs Density

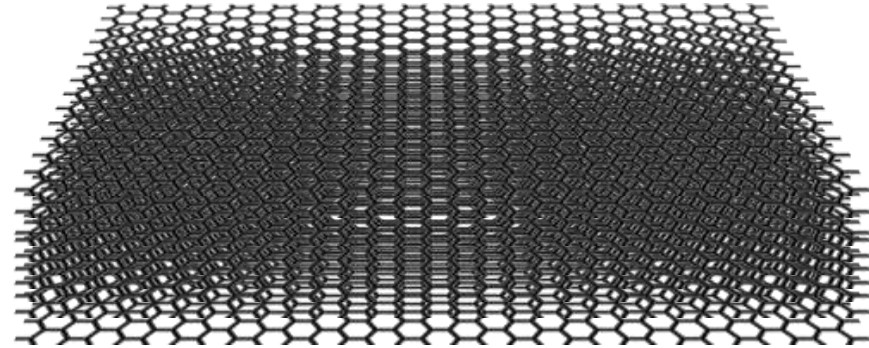


This is so new even the descriptive language is evolving...

Single Crystal Graphene is one layer of graphene



Multiple layers of Single Crystal Graphene make a new kind of material, a form of synthetic graphite we will not have seen before:
A Van der Waals Homostructure



ISEC are already calling this multi-layered tether material 'Nixene' even before it has been made

Single-Crystal Graphene ('Nixene')



Comparison with target : MATERIAL PROPERTIES

	CNT Target	NIXENE
Yield Strength	49.3 GPa	124 GPa
Density	1300 kg m ⁻³	2260 kg m ⁻³
Specific Strength	37.9 MYuri	54.5 MYuri
Young's Modulus	1000 GPa	1000 GPa

Sources :

CNT : ISEC studies based on "Space Elevators : An Assessment of the Technological Feasibility....", IAA 2013

Nixene : A. Nixon, July 2018 : atomic layer separation = 0.34 nm

CNT = Carbon Nanotubes

Single-Crystal Graphene ('Nixene')



Impact on Earth Space Elevator Design

No change in climber loads or safety margin (40%),

Tether dimensions : 100,000 km long x 1m wide

	CNT Target	NIXENE
Tether Thickness at Earth Port	10.5 micron	4.2 micron 12,333 atomic layers
Tether Thickness at GEO	64 micron	14.7 micron 43,167 atomic layers
Taper Ratio	6:1	3.5:1
Total Tether Mass	6540 tonnes	2740 tonnes
Apex Anchor Mass	1900 tonnes	1455 tonnes
Working Stress	35.2 GPa	88 GPa
Nominal Strain	3.5 %	8.8 %

Based on calculations by J Knapman and P Robinson

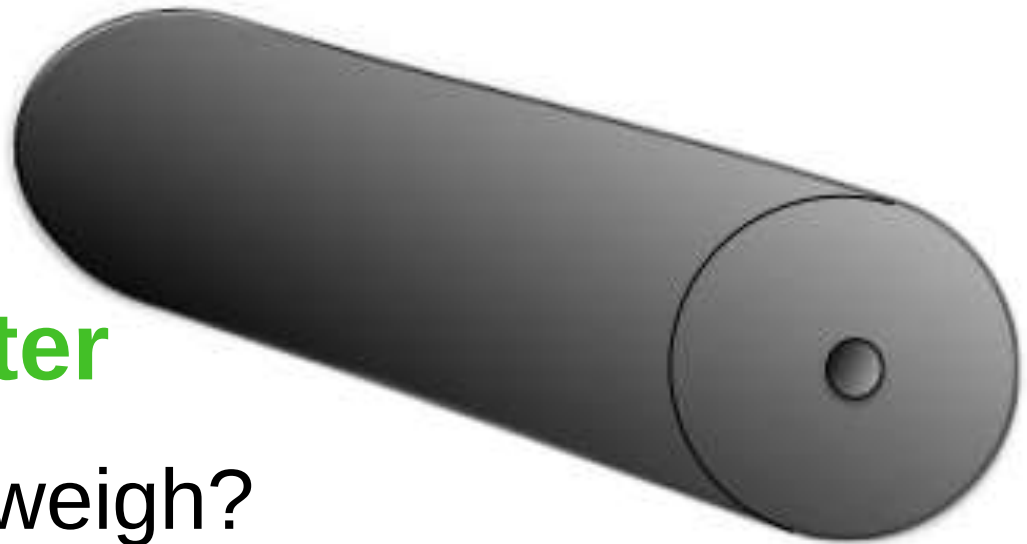
How might a space elevator tether be constructed from Nixene?

Feasibility of building the tether...

How big is a reel of single crystal graphene 100,000km long?

20mm core
1000mm wide

300mm Diameter



How much would it weigh?

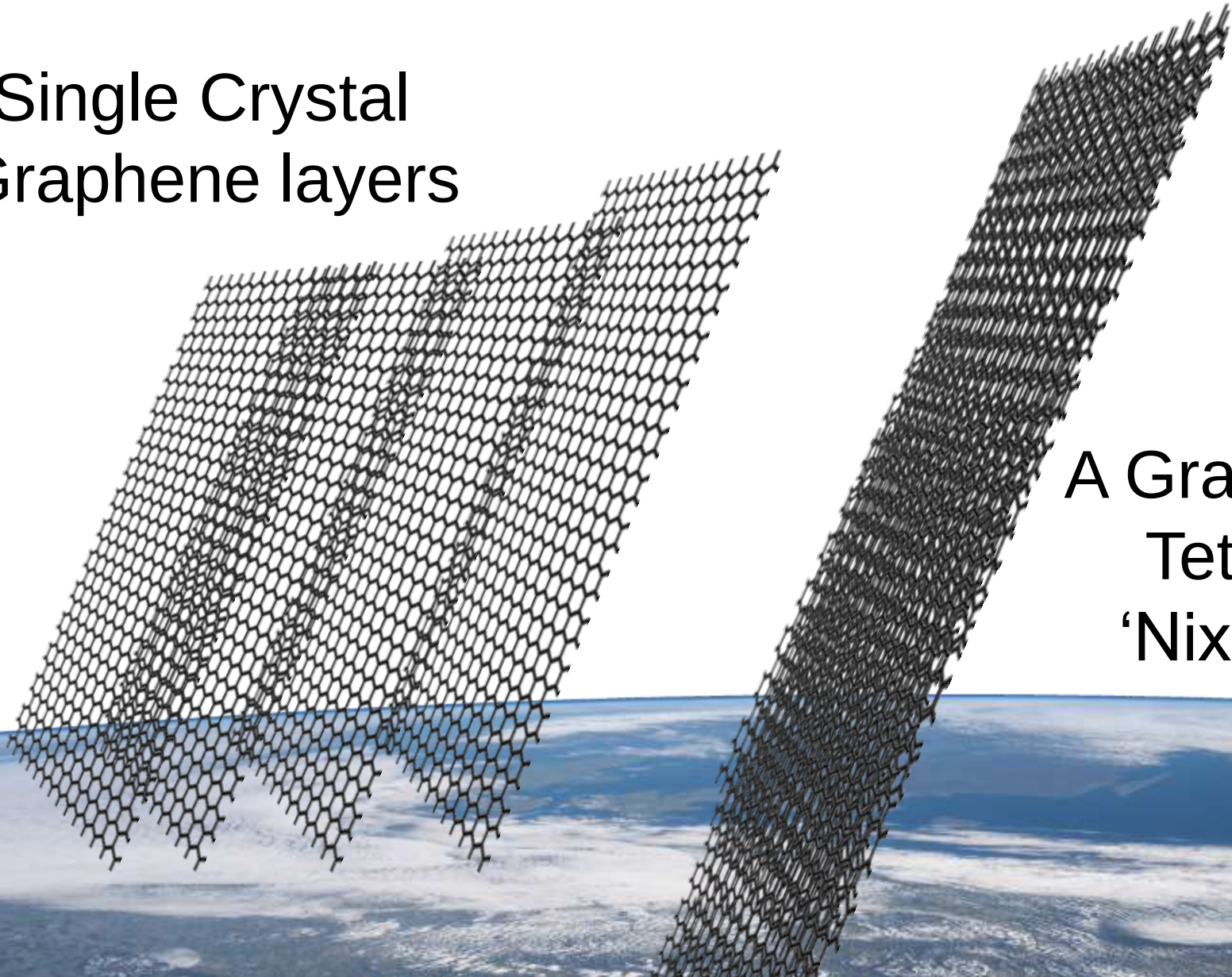
77kg

Dr. Peter Clark helped with the calculations...

<https://www.linkedin.com/in/peter-clark-30ab9221/>

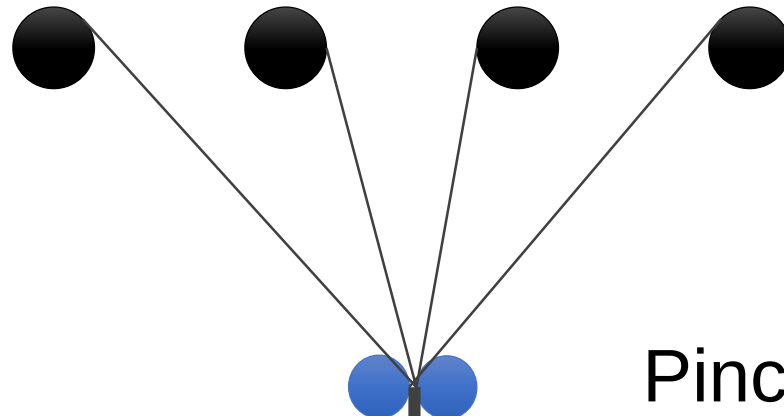
Combine the tether layers in orbit...

Single Crystal
Graphene layers



A Graphitic
Tether
'Nixene'

Combine the tether layers in orbit...



A diagram illustrating a space-based manufacturing concept. A vertical black line, representing a tether, extends from the Earth's surface to a point in space. At this point, two blue circles represent 'Pinch rolls forming Multilayer graphene (Graphitic) tether'. From this junction, four lines radiate upwards and outwards to four black circles, which represent 'Single crystal graphene roll cassettes'. The background shows a view of the Earth from space, with the horizon and clouds visible.

Single crystal graphene
roll cassettes

Pinch rolls forming
Multilayer graphene
(Graphitic) tether
'Nixene'

The tether project technology roadmap

R1. Proof of concept

Make single crystal graphene
By a continuous process

3 years
\$10
Million

R2. Prototyping

Make graphene at metre scale
Develop production machines
and process sensor controls

2 years
\$400
Million

R3, R4. Manufacturing

Build the factories and
make the graphene layers

6 years
\$5 Billion

R5, R6. Testing

Testing of 1000km lengths of tether in
near earth orbit Then longer lengths and
operational issues

2 years
\$1.3
Billion

5-10 years
\$9.8 Billion

R7. Production, launch, deployment

5 years
\$10
Billion

Current Estimate \$26.5 Billion and 26 years

Is a tether made from single crystal graphene feasible?

Current commercial nanoplate graphene cannot be used to make a tether.

However, 500mm of single crystal graphene has been made 13 years after graphene first isolated.

Layered single crystal graphene is yet to be made but we know how to do this and the material is already being called Nixene

YES

Graphene tether material really is possible within our lifetimes.

Space Elevator Tether

Single crystal sheet graphene sheet is strong enough
To make this a reality



**The International Space
Elevator Consortium**

Thank you for your time

Adrian Nixon

Nixene Ltd