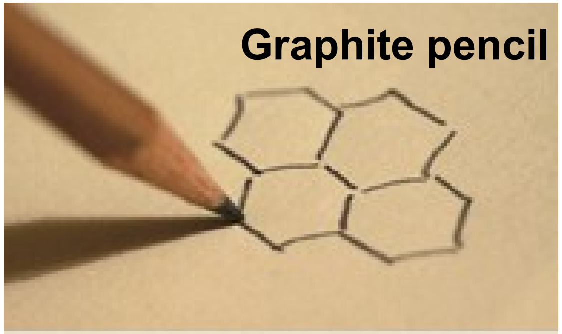
Real & Fictitious Magnetic Fields in Strained Graphene

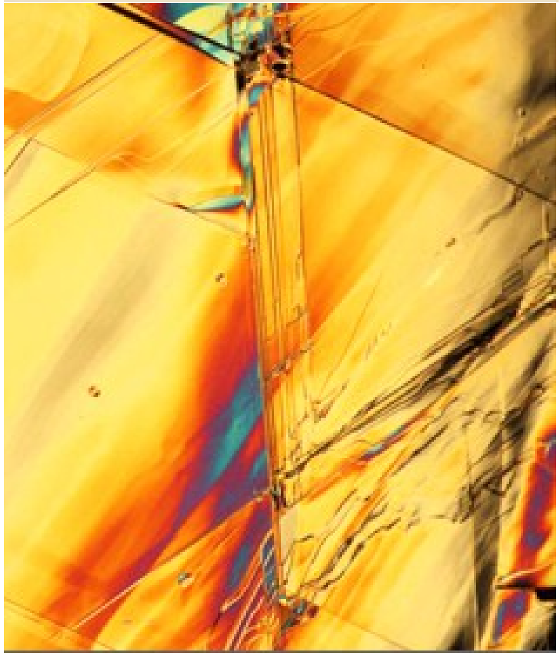
Natalie Whitehead
Year 3 MPhys Student
Supervisor: Eros Mariani
Quantum Systems & Nanomaterials

Background image credit: The University of Manchester

Presentation Outline

- What is Graphene?
- How can a 2D structure exist?
- How is Graphene produced?
- Graphene's special properties
- Strained Graphene
- Project progress so far
- Next steps





Surface of graphite crystal

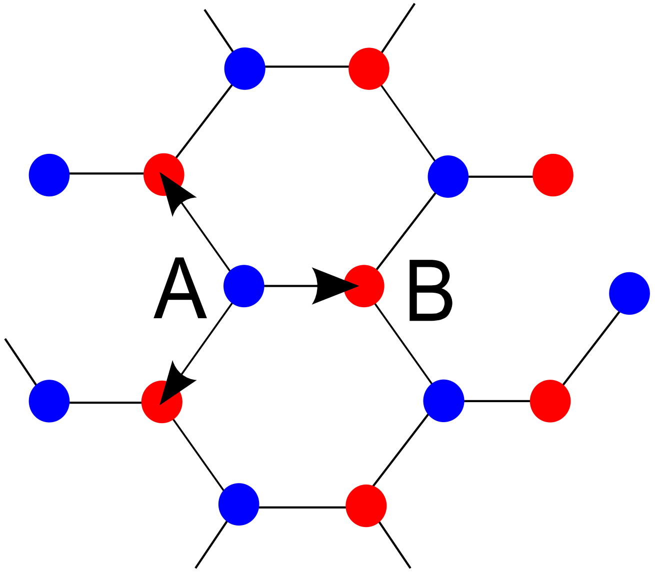
Images credit: http://emps.exeter.ac.uk/physics-astronomy/research/graphene/

UNIVERSITY OF EXETER

What is Graphene?

- 2D carbon honeycomb lattice [1] with 2 sub-lattices (A & B)
- The only 2D conducting membrane (so far!) [2]

Landau & Peierls: 2D materials can't exist! [3][4]



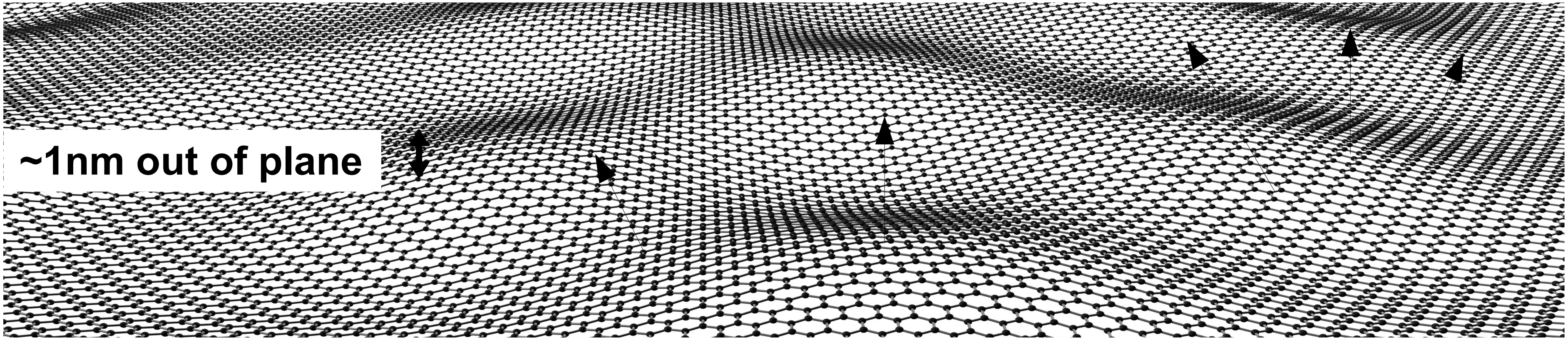
[1]: Geim, A. K. & Novoselov, K. S. The rise of graphene. *Nature Materials* 6, 183 - 191 (2007)
[2]: Mariani, E. et al. Fictitious gauge fields in bilayer graphene. Phys. Rev. B 86, 165448 (2012)
[3]: Landau, L. D. Zur Theorie der phasenumwandlungen II. *Phys. Z. Sowjetunion* 11, 26–35 (1937)
[4]: Peierls, R. E. Quelques proprietes typiques des corpses solides. *Ann. I. H. Poincare* 5, 177–222 (1935)

UNIVERSITY OF EXETER

The Predicted Instability

- Thermal fluctuations destroy long term order [1]

  => perfect crystal in 2D too unstable...
- But nearly perfect 2D crystal in 3D space can exist!
- Graphene's inherent corrugation seems to provide stability [1][2]

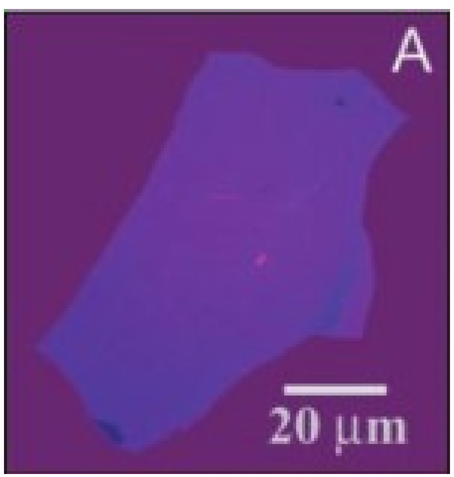


[1]: Meyer, J.C. et al. The structure of suspended graphene sheets. *Nature* 446, 60-63 (1 March 2007)
[2]: Fasolino, A. et al. Intrinsic ripples in graphene. *Nature Materials* 6, 858 - 861 (2007)
Image credit: Jannik Meyer. Obtained from: http://www.condmat.physics.manchester.ac.uk/imagelibrary/

UNIVERSITY OF EXETER

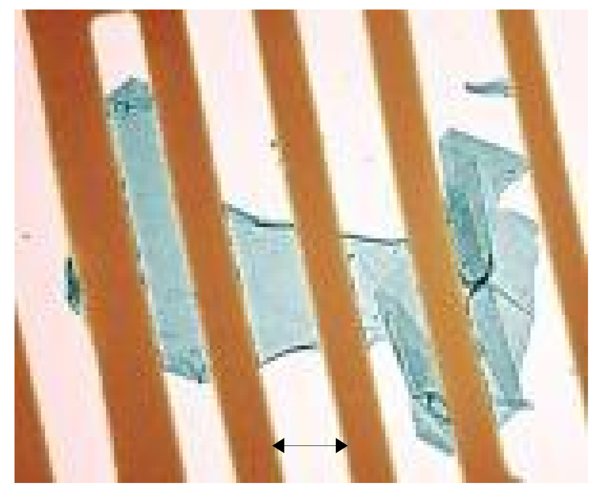
Making Graphene

- 'Mechanical Exfoliation' using Scotch tape – still best method! [1]
- Growth on a substrate – samples generally poorer quality than exfoliated sheets [2]



White light photo of graphene visible on oxidised Si wafer

Suspended graphene sheet (TEM image)

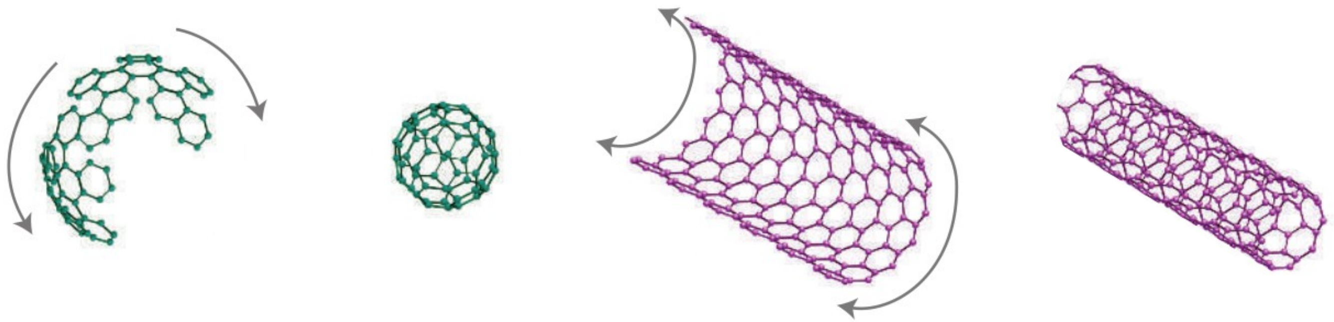


~500nm

[1]: Geim, A. K. & Novoselov, K. S. The rise of graphene. *Nature Materials* 6, 183 - 191 (2007)
[2]: 'Challenges in Graphene Technology' http://www.graphene.manchester.ac.uk/research/challenges/
Image credit (left): Novoselov, K. S. et al. Science 306, 666–669 (2004).
Image credit (right): Jannik Meyer. From: http://www.condmat.physics.manchester.ac.uk/imagelibrary/

Special Properties

- High thermal conductivity: 5000 $Wm^{-1}K^{-1}$ [1]
- High breaking strength: 42N/m [1]
- High mobility: >200,000 $cm^{2} \cdot V^{-1}s^{-1}$ at 300K [2]
- High crystal quality (~1 defect per μm) [2]
- Flexible (despite high Young Modulus of ~1TPa)

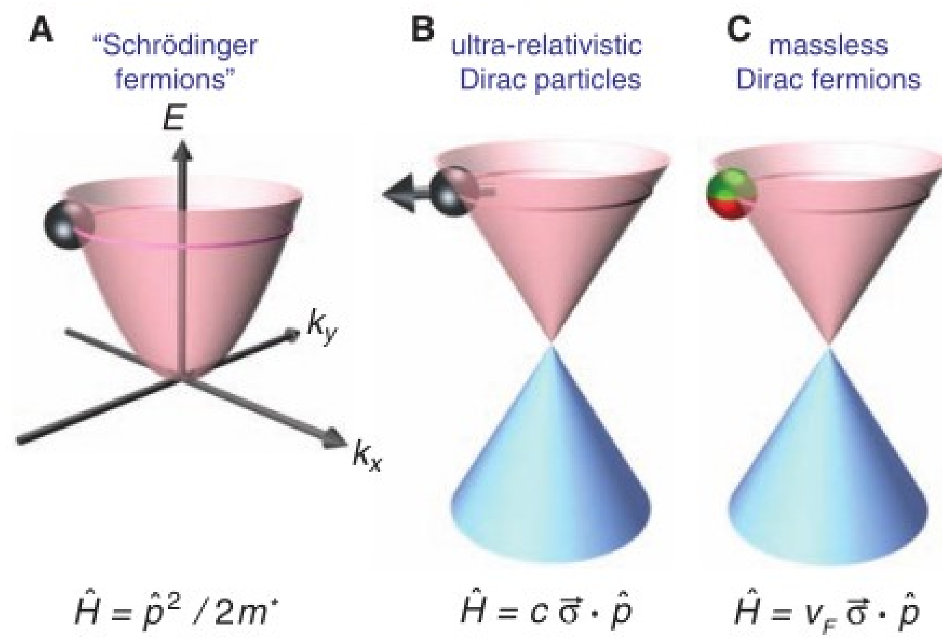


[1]: http://www.nobelprize.org/nobel_prizes/physics/laureates/2010/advanced-physicsprize2010.pdf
[2]: Geim, A. 'Graphene: Magic of Flat Carbon' http://www2.avs.org/conferences/icnt/pdfs/speakers/geim.pdf
Image adapted from: Geim, A. K. & Novoselov, K. S. The rise of graphene. *Nature Materials* 6, 183 - 191 (2007)

"CERN on one's desk"[1]

- **Electrons → Massless Dirac Fermions [2]**

Electron interaction with honeycomb lattice
=>
massless quasi-particles described by **Dirac Equation** (not Schrödinger Equation)

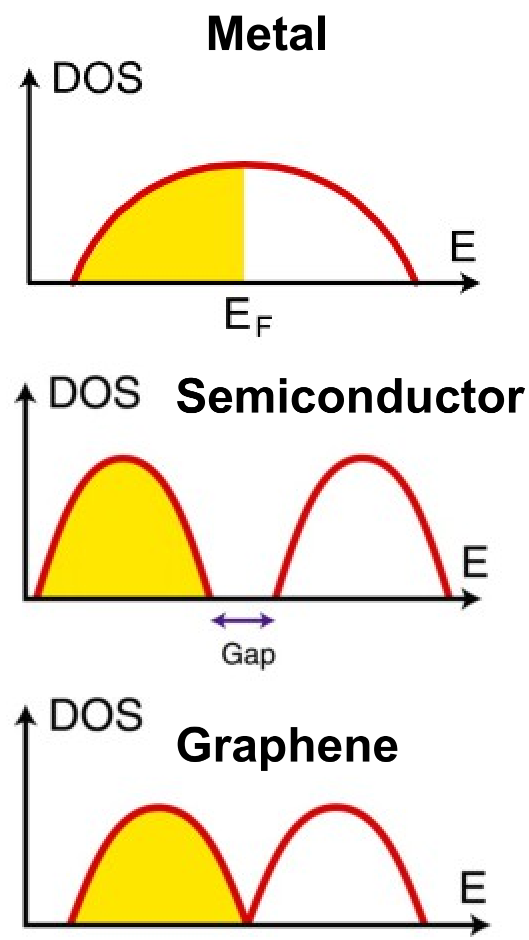


[1]: Katsnelson, M.I. *Graphene - Carbon in Two Dimensions.* New York: Cambridge University Press (2012)
[2]: Geim, A. Graphene: Status and Prospects. *Science* 324 (5934): 1530-1534 (2009)
Image credit: from [2]

Why Should We *Strain* Graphene?

- Graphene has zero-band gap
  =>
  limitations for nanotechnology – eg: (traditional) transistors need a band gap [1]

- Applying **non-uniform** strain => control of electrons & hence band gap [2]

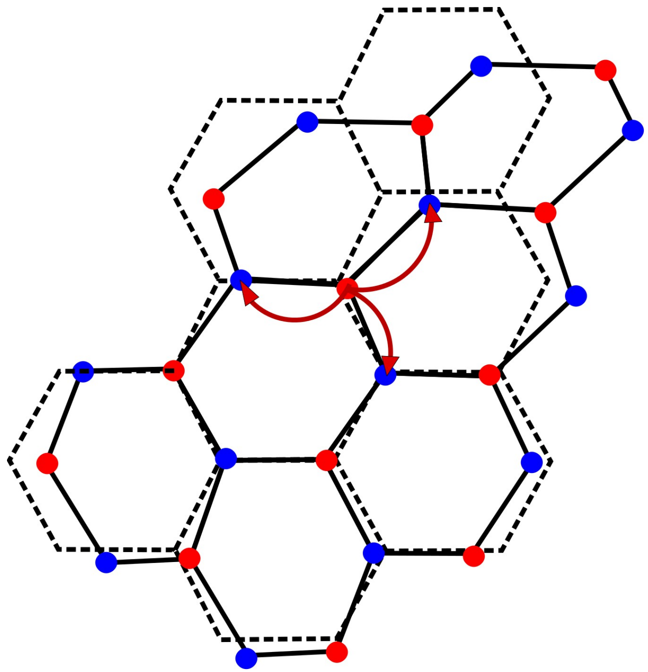


[1]: http://www.technologyreview.com/view/518426/how-to-save-the-troubled-graphene-transistor/
[2]: Gui, G. et al. Phys. Rev. B 78, 075435 (2008).
Image credit: 'Quantum Theory of Graphene' lecture slides, University of Pennsylvania, from: www.physics.upenn.edu/~kane/pedagogical/295lec3.pdf

UNIVERSITY OF EXETER

Strain-Induced Gauge Fields

- Massless Dirac Hamiltonian [1



No strain:

$$\hat{H} = \begin{pmatrix} 0 & v_F(p_x - ip_y) \\ v_F(p_x + ip_y) & 0 \end{pmatrix}$$

With strain:

$$\hat{H} = \begin{pmatrix} 0 & v_F(p^* + A^*) \\ v_F(p + A) & 0 \end{pmatrix}$$

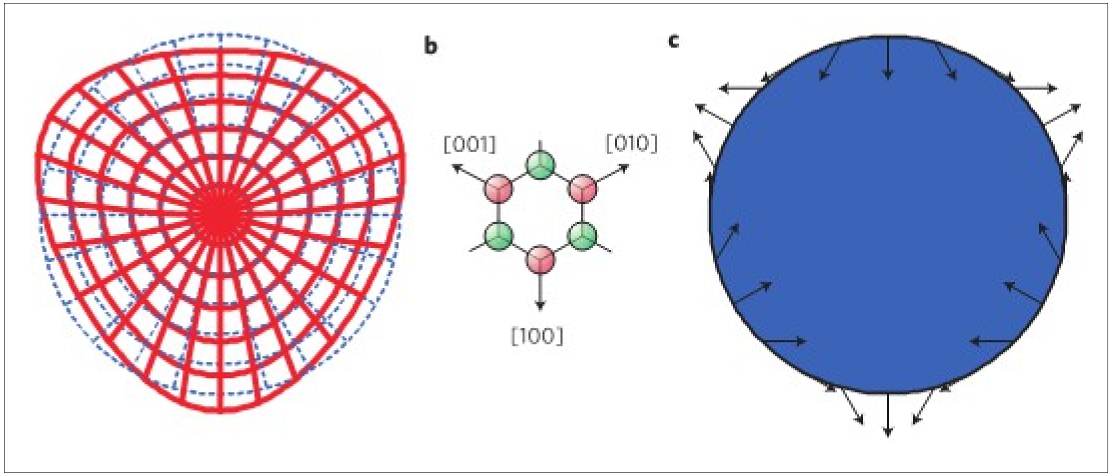
Strain produces a (fictitious, magnetic) vector potential!

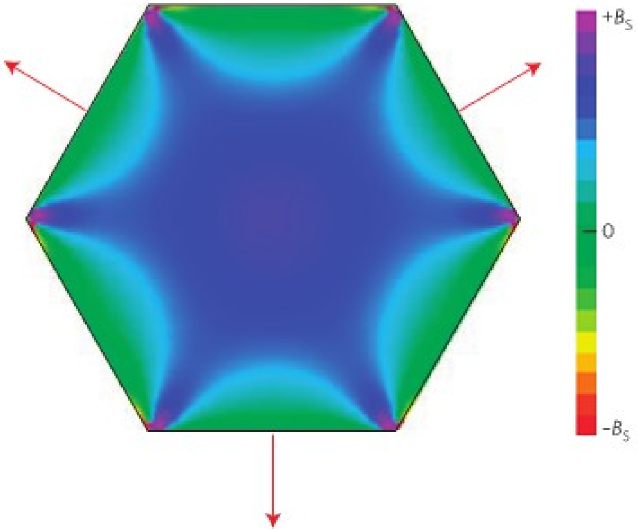
UNIVERSITY OF EXETER

[1]: Castro Neto, A. H. The electronic properties of graphene. *Rev. Mod. Phys*. 81, 109–162 (2009)

In-Plane Strain of Graphene

Guinea et al: fictitious fields over 10T





Left: uniform fictitious B fields can be created by strain applied as shown.
Right: strain that is more easily applied experimentally – fairly uniform fictitious B field in centre of hexagon.

UNIVERSITY OF EXETER

Image credit: Guinea, F. et al. Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering. *Nature Physics* 6, 30 - 33 (2010)

Out-of-Plane Strain of Graphene

Pyramid-shaped graphene nanobubbles: fictitious fields of ~ **350T**

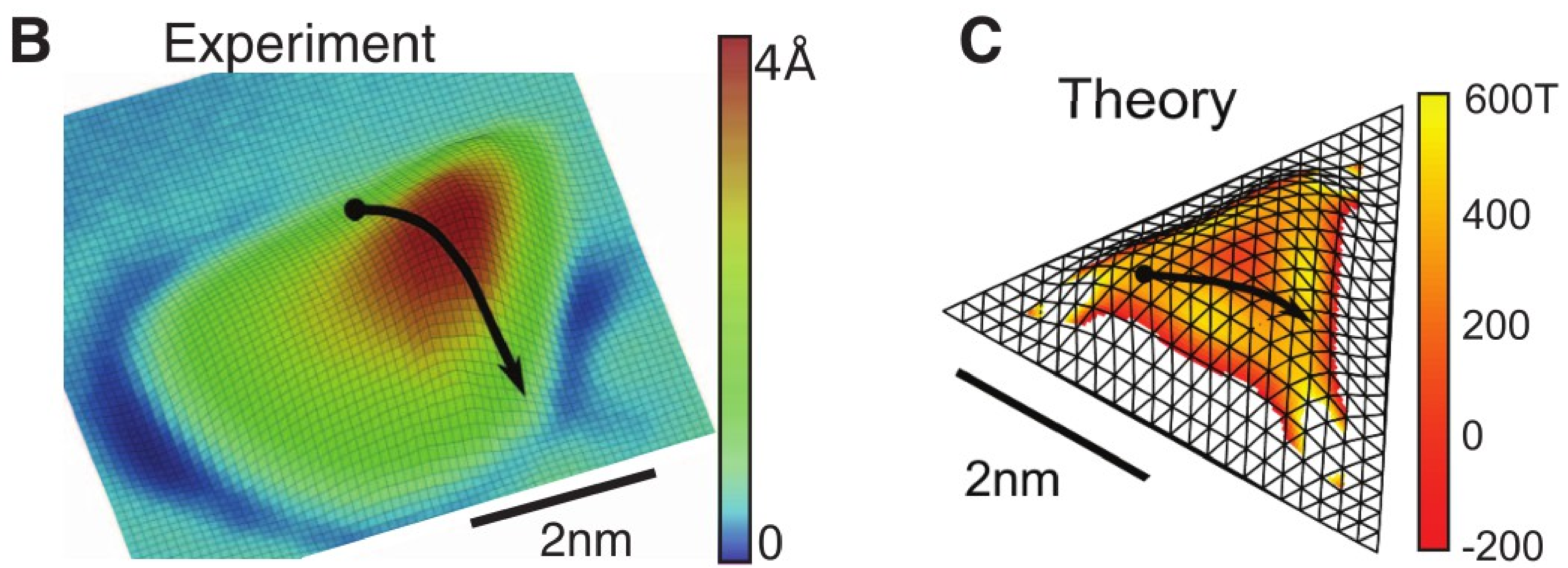
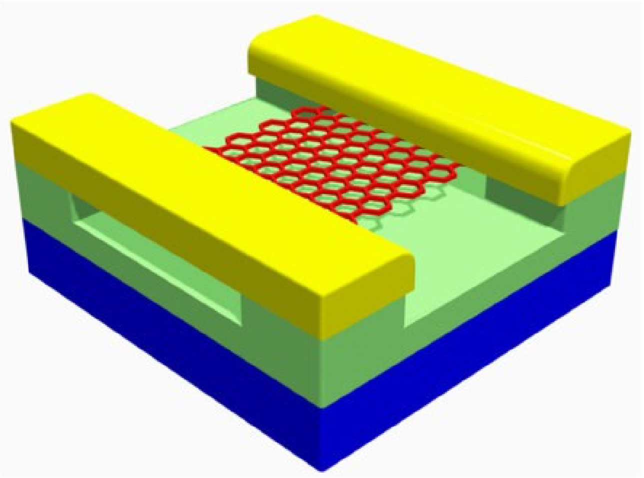


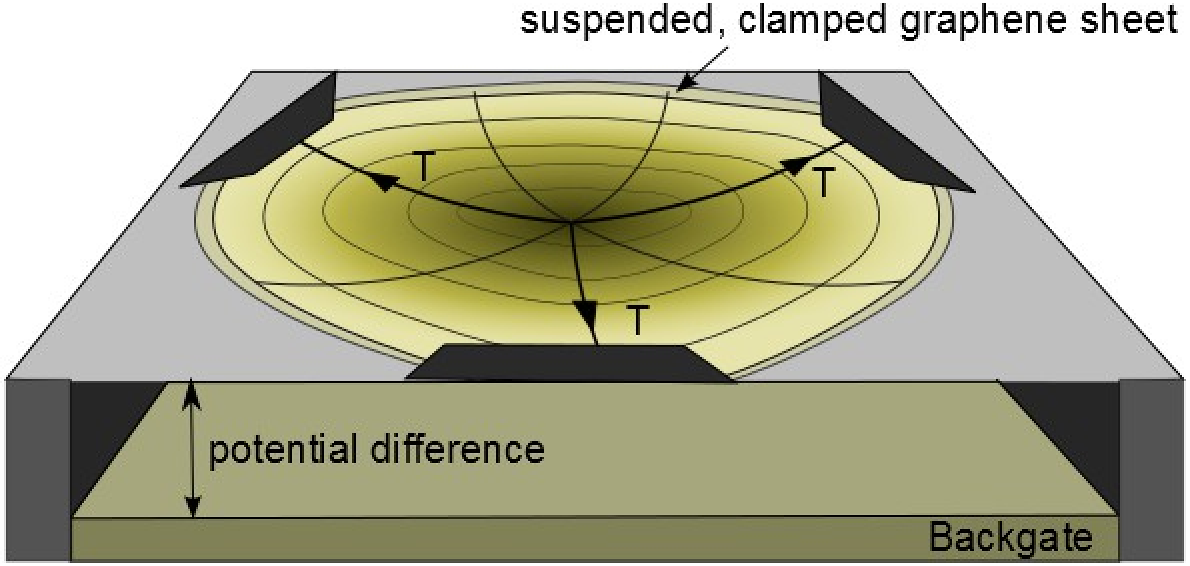
Image credit: Levy, N. et al. Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles. *Science*329. 544 (2010)

UNIVERSITY OF EXETER

Our Gedankenexperiment

Graphene sheets have been successfully suspended in experiments





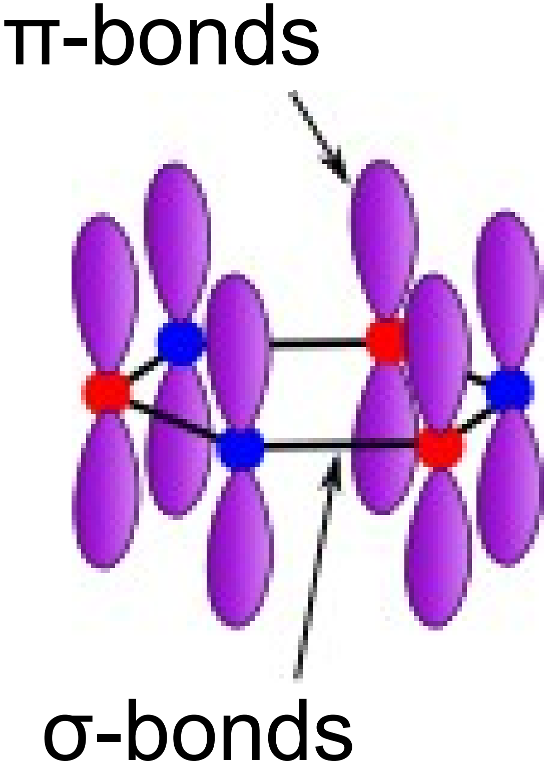
We will describe analytically:

How applied voltage induces (non-uniform) triangular strain

Image credit (top right): http://physicsworld.com/cws/article/news/2009/sep/29/graphene-works-as-a-highly-sensitive-mass-detector

Progress so Far: Tight Binding Method

- First solved for graphite by Wallace in 1947 [1]
- π-bonds contribute to conduction
- Electrons 'hop' to nearest neighbours



[1] Wallace, P. R. *The band theory of graphite*. Phys. Rev. 71, 622–634 (1947).

UNIVERSITY OF EXETER

Tight Binding: 1 Atom per Unit Cell

Hamiltonian:

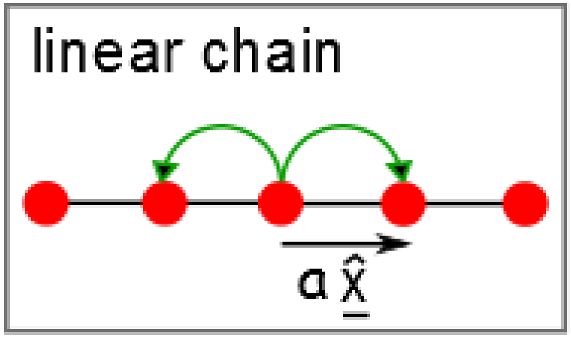
$$\hat{H} = -t \sum_j (|R_j >< R_j + a|)$$

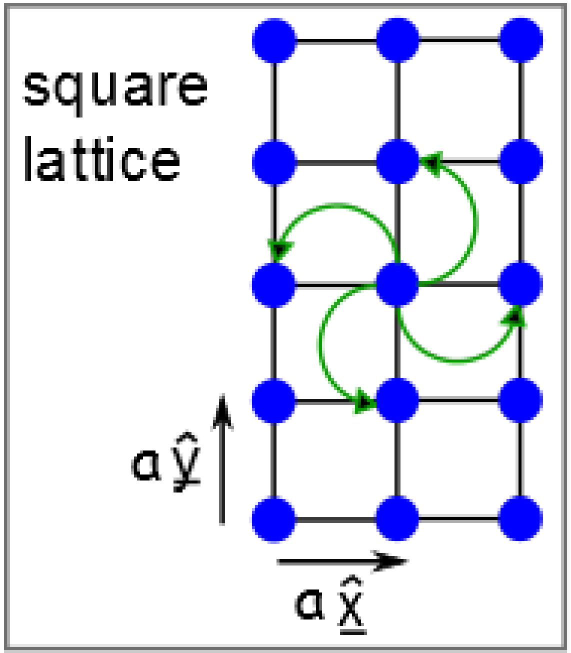
Wavefunction:

$$|\Psi_k(\mathbf{r}) >= \sum_j \left(c e^{i\mathbf{k}\cdot\mathbf{R}_j} |R_j > \right)$$

Solve Schrödinger Equation:

$$\hat{H}|\Psi >= E|\Psi >$$



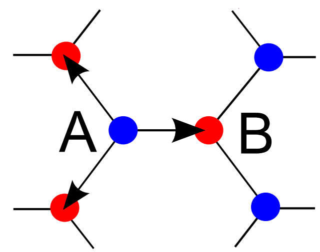


UNIVERSITY OF EXETER

Tight Binding: Graphene (Two Inequivalent Sublattices)

$$\hat{H} = -t \sum_{R_A} \sum_{i=1}^{3} \{|R_A >< R_A + d_i|\} - t \sum_{R_B} \sum_{i=1}^{3} \{|R_B >< R_B - d_i|\}$$

Sum over sublattice A



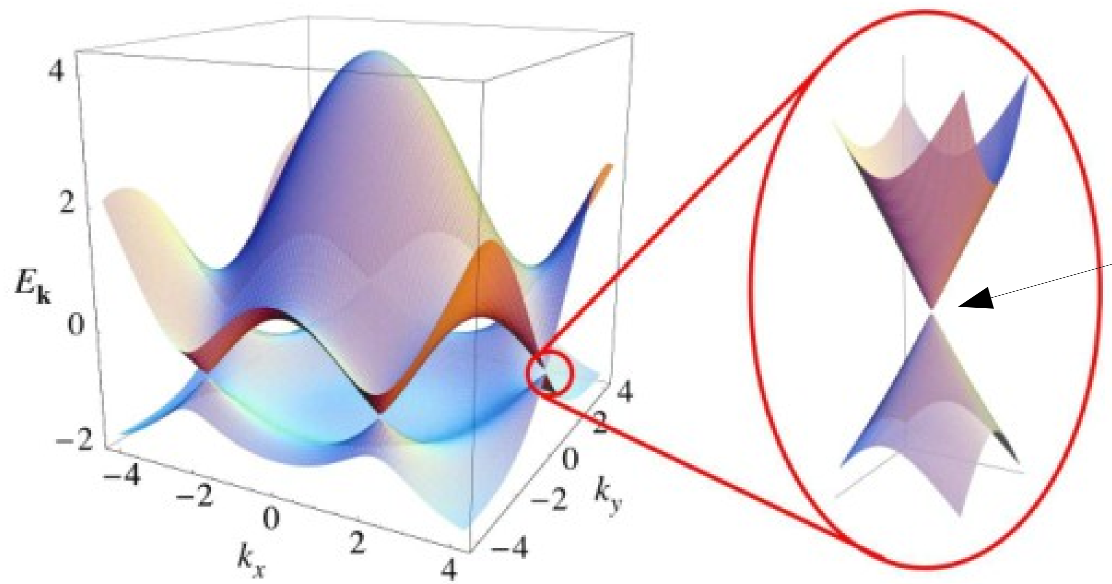
Sum over sublattice B

$$|\Psi_k(\mathbf{r}) >= \sum_{R_A} (c_A e^{i\mathbf{k}.\mathbf{R}_m} |R_A >) + \sum_{R_B} (c_B e^{i\mathbf{k}.\mathbf{R}_m} |R_B >)$$

Image credit: www.physics.upenn.edu/~kane/pedagogical/295lec3.pdf

Tight Binding: Dispersion Relation for Graphene

$$E(\mathbf{k}) = \pm t\sqrt{1 + 4cos\left(\frac{\sqrt{3}ak_y}{2}\right)cos\left(\frac{3ak_x}{2}\right) + 4cos^2\left(\frac{\sqrt{3}ak_y}{2}\right)}$$



Next step: probe deeper to describe form of E(**k**) near Dirac Points

Image credit: Castro Neto, A. H. et al. The Electronic Properties of Graphene. Rev. Mod. Phys. 81, 109 (2009)

Next Steps

- Resolve detail of E(k) - Dirac Points
- Understand electron propagation
- Predict 0% backscattering probability
- Membrane deformation theory
- Fictitious gauge field theory

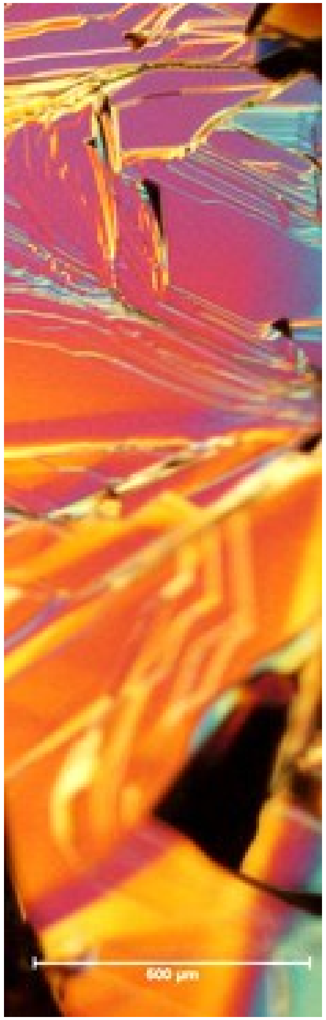


Image credit: http://emps.exeter.ac.uk/physics-astronomy/research/graphene/

UNIVERSITY OF EXETER