A. K. Geim (2011), *Nobel Lecture: Random walk to graphene*, Reviews of Modern Physics, **83**, 851

https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.83.851

This week we're looking at a different style of paper: a review article. A review article is written to give an overview of a field or topic of research and so they're particularly useful if you're new to a field. They are written with a wider audience in mind and so generally start with less assumed knowledge of the reader, but they provide lots of references to the technical pieces that constitute the key research in a particular field. This review in particular is written for the widest possible audience since it is an adaptation of the speech given when Andre Geim and Konstantin Novoselov received the 2010 Nobel Prize for physics for their discovery of graphene. This article gives an insight into the life of scientist and how they became a Nobel Prize winner.

SKIM-READ QUESTIONS

As with last week, take a brief skim read through the paper and make a list of some of the main things we need to be clear of before we read the paper in depth. Check you understand these key ideas by answering a few of what you consider to be the most important questions. As a suggestion, we think the key things you need to know to get the most out of this article are:

1. What is graphene?
2. What is microfabrication?
3. What is diamagnetism?
4. What is the electric field effect?

Either answer these 4 questions (or the ones you wrote) in as simple terms as possible after a little bit of research (remember to cross check what you find makes sense across more than one website).

Below are the questions to answer as you go along for each section – some of the sections we are going to skip so take note.

Zombie management

(P1, C1) '*Web of Science soberly reveals that the papers were cited twice*'. What is a citation and why is it sobering that they were only cited twice? (P1, C1) What does Geim mean by the phrase 'zombie project'?	

(P1, C1) Thinking back to week 3: '*the superconductor served only to condense an external magnetic field into an array of vortices*'. What type of superconductor must this have been? (P1, C1) What does inhomogenous mean? (P1, C1) What is electron transport and why is it affected by a magnetic field?	

One man's junk, another man's gold

(P1, C2) What does 'submicron' mean? (P1, C2) What is a '*h index*'? (P1, C2) What does mesoscopic mean? How does this link to Anderson's paper *More Is Different* from week one? (P1, C2) What is a 2D electron gas?	

We are probably not familiar with all of the effects and techniques that Geim mentions – quantum point contacts, resonant tunneling, the quantum Hall effect, molecular beam epitaxy, electron-beam lithography etc. but that's okay. They're not crucial to our understanding of the article so we can ignore them for now. It takes time to realise which bits are important and which bits we can ignore for now – we just need to gain experience at reading papers.

Dutch comfort

(P2, C1) Why would scientists want to study the individual vortices within a type-II superconductor (think back to week 3).	

A spell of levity

(P2, C2) In the first paragraph of '*a spell of levity'* what does Geim highlight about the political nature of science? (P2, C2) What advantage did Geim have in studying 'magnetic water'? (P2, C2) What is diamagnetism? (P2, C2) Why did the water 'float' inside the 20T magnetic field?	

(P2, C2) Draw a force diagram for a droplet of water inside Geim's magnetic field. (P2, C2) Why can't you see levitating water with a normal magnet? (P3, C1) Why do you think a frog can also be levitated within a magnetic field?	

Friday night experiments

(P3, C2) A van der Waals force is an intermolecular force – what does this mean? (P3, C2) Van der Waals forces are incredibly weak. How can such weak forces manage to suspend a gecko? (P3, C2) Why would a large diamagnetic response be an indicator of possible superconductivity? (Think back to week three)	

Mancunian way

(P4, C1) How have Geim's previous experiences in research shaped his attitudes to spending his grant money?	

Three little clouds

(P4, C2) In terms of free electrons, what is the difference between a metal and a semiconductor? (P4, C2) What is the electric field effect (also known as the field effect)? (P4, C2) In terms of free electrons, what is the difference between a metal and a semiconductor? (P4, C2) In terms of the number of free electrons, what is the difference between a metal and a semimetal? (P5, C1) What is a carbon nanotube? What is its relationship to graphene?	

(P5, C1) What was Geim hoping to achieve by getting his student to look into thin films of graphite?	

Legend of Scotch tape

(P5, C1) What is pyrolytic graphite (or pyrolytic carbon) and what's its advantage over natural graphite when trying to produce graphene? (P5, C1) In polishing the sample, what were they hoping to achieve? (P5, C1) What might the advantage of highly oriented pyrolytic graphite be over the sample that they originally used? (P5, C2) How does sellotape create thinner samples of graphite than polishing? (P5, C2) If you've read any Shakespeare, compare and contrast the styles of the bard with Geim in this article so far (this is not a serious question...).	

(P6, C1) What is a substrate in crystallography?	
(P6, C1) Why does being optically transparent indicate that a sample is thin?	
(P6, C1 and Figure 2d) Describe what is shown in Figure 2d.	
(P6, C1 and Figure 2d) 50µm is a difficult size to imagine. Find a comparison to understand how big 50µm is.	

Eureka moment

(P6, C1) Rather than using sellotape to create graphene, what does Geim describe as his real Eureka moment?	
(P6, C2) In the simplest of terms, what does Geim mean when he talks about moving 'from multilayers to monolayers and from hand-made to lithography devices'.	

(P6, C2) How did Geim and his team ensure that any of their conclusions about the electrical properties of graphene were valid? (P6, C2) Studying 50 samples doesn't initially sound too taxing... why is it such hard work. (P6, C2) What does Geim highlight about the review process for getting articles published?	

Defiant existence

(P7, C1) What does Geim mean by a continuous monolayer? (P7, C1) Why does a system often prefer to create small regions rather than a continuous layer? (P7, C1) Why was it predicted that small, flat graphene sheets were unlikely to occur?	
The third argument for why the existence of graphene is surprising is a little more involved so we won't dwell on it. To grow a sample, the atoms need cool into a stable arrangement. If we're trying to grow a 2D sample, this is problematic as thermal fluctuations have a greater effect. Combined with the need for a substrate to grow it on, this limits the predicted size of graphene samples.	

(P7, C1) What is a theoretical disadvantage of graphene when it comes its existence in air? (P7, C1) Summarise (in as much detail as you feel comfortable with) the reasons that people would have been surprised that small, flat, continuous, monolayer sheets of graphene exist.	

For our purposes, we can largely ignore the section *Graphene incarnations* (P8 and most of P9, C1), but you may wish to read it for your own interest.

Planet graphene (The Greek letters spell 'planet')

(P9, C2) Why does Geim believe people were so interested in his paper? (P9, C2) Looking back, what is a typical value for the percentage change in the number of electronic carriers if a material displays the electric field effect? (P9, C2) What does 'charge carrier mobility' mean? (P9, C2) Why does Geim refer to 'ballistic transport' for graphene? (P9, C2) Summarise some of the remarkable electronic properties of graphene.	

The section '*Magic of flat carbon'* gives some of the newer findings about graphene's capabilities. These are a little more specialized and aren't discussed in enough detail for us to truly understand so we'll leave our questions for this section.

Ode to one

(P10, C1) Other than its electronic properties, in what other ways in graphene remarkable? (P10, C2) Why is graphite (and bilayers of graphene) much weaker than monolayer graphene? (P10, C2) What reason does Geim give for graphite (and multilayer graphene) having significantly different electronic properties?	

SUMMARY QUESTIONS (submit your answers to these questions to thomas.millichamp@warwick.ac.uk)

Send in your answers to the four **SKIM-READ QUESTIONS** (or your own ones) from the top of the sheet and then answer:

What makes graphene such a momentous material?

Which piece of Geim's research stood out most to you? Summarise it in three sentences or less.

What have you learned about the workings of a scientific research group from this article?

Why do you think Geim believes that *"Chances of success are much higher where the field is new"*? Is there any reason why this might not be the case?

Further Reading

More information on the levitation of frogs can be found here

https://physicstoday.scitation.org/doi/pdf/10.1063/1.882437

Discovery and characterisation of graphene (this is actually a paper in the journal *Science* but a version is available on the arXiv that does not require an academic subscription)

https://arxiv.org/pdf/cond-mat/0410550.pdf

A more detailed review of graphene by Geim and Novoselov can be found here

https://arxiv.org/ftp/cond-mat/papers/0702/0702595.pdf