PHYS 3313 – Section 001
Lecture #24

Monday, Apr. 21, 2014
Dr. Jaehoon Yu

- Liquid Helium
- Superconductivity Theory, The Cooper Pair
- Application of Superconductivity
- Nano-technology
- Graphene

Announcements

- Reminder Homework #6
  - CH7 end of chapter problems: 7, 8, 9, 12, 17 and 29
  - Due on Wednesday, Apr. 23, in class
- Quiz #4
  - This Wednesday at the beginning of the class
  - Covers CH6 through what we finish today
- Final exam is 11am – 1:30pm, Monday, May 5, SH103
  - Comprehensive exam covering from CH1.1 to what we finish this Wednesday + appendices 3 – 7
  - BYOF: one handwritten, letter size, front and back
    - No derivations or solutions of any problems allowed!
- Reading assignments
  - CH10.1, 10.3 and 10.4
- Please be sure to fill out the feedback survey.
- Colloquium this Wednesday at 4pm in SH101

Reminder: Research Project Report

1. Must contain the following at the minimum
   - Original theory or Original observation
   - Experimental proofs or Theoretical prediction + subsequent experimental proofs
   - Importance and the impact of the theory/experiment
   - Conclusions
2. Each member of the group writes a 10 (max) page report, including figures
   - 10% of the total grade
   - Can share the theme and facts but you must write your own!
   - Text of the report must be your original!
   - ***Due Mon., Apr. 28, 2014***

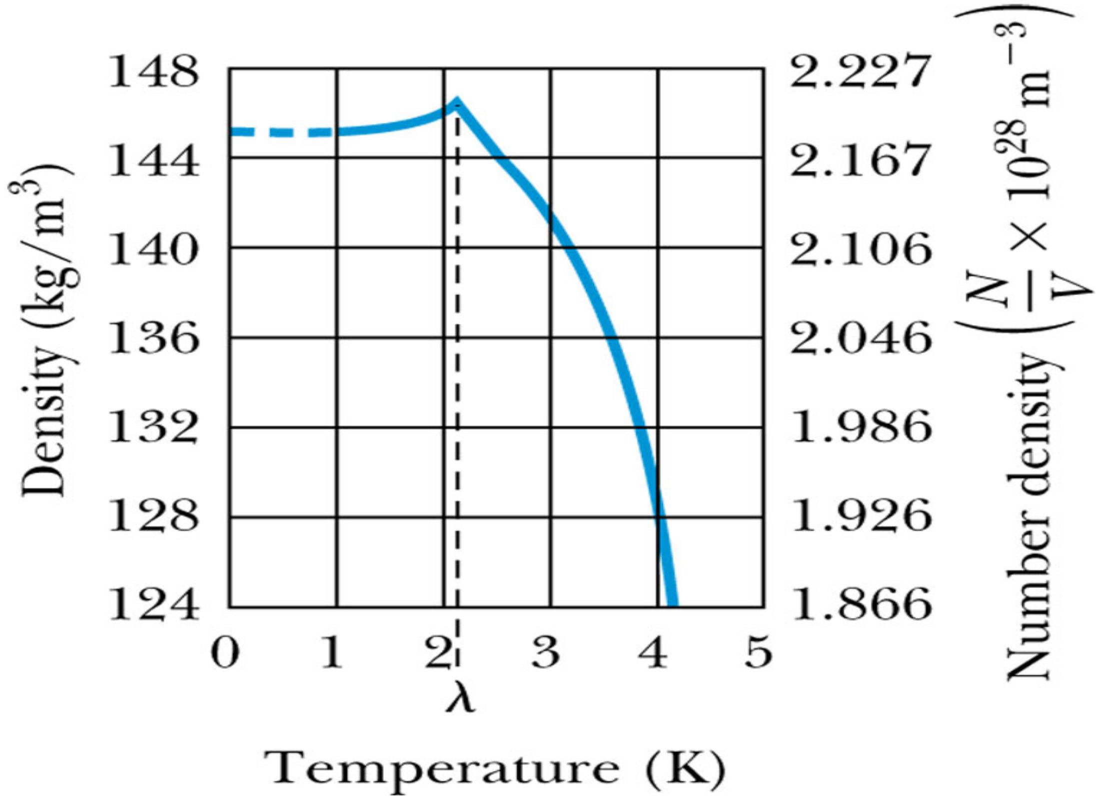
Group Number	Reseasrch Group Members	Research Topic # & Title	Presentation Date and Order
1	J. Paul Carpenter, Erwin Christopher, Matthew Gartman, Hope Montgomery	7. Rutherford Scattering	4/30 - 2
2	Tyler Anway, Jay Lundy	3. The Photo-Electric Effect	4/28 - 3
3	John Crouch, Ryan Jones	2. Michelson-Morley Experiment	4/30 - 4
4	Christopher Dunn, Garrett Leavitt, Giang Tran	4. The property of molecules - the Brownian Motion	4/28 - 2
5	Cole Boutwell, Oscar Rodriguez, Kevin Strehl, Hector Zapata	1. Black-body Radiation	4/28 - 4
6	Soha Aslam, Arthur D'Auteuil, Andrew Mcginnis, Jose Montelongo	8. Super-Conductivity	4/28 - 1
7	Jesus Alcala, Derric Edwards, Ronald Musser, Cody Tipton	5. Compton Effect	4/30 - 1
8	Austin Mcdonald, Robert Moore, Panpiroon Punnakanta, Dalton Sussumes, Troy Piqq	6. Discovery of Electron	4/30 - 3

Research Presentations

- Each of the 8 research groups makes a 12+3 min presentation
  - 12min presentation + 3min Q&A
  - All presentations must be in power point
  - I must receive all final presentation files by 8pm, Sunday, Apr. 27
    - No changes are allowed afterward
  - The representative of the group makes the presentation followed by all group members' participation in the Q&A session
- Date and time:
  - In class Monday, Apr. 28 or in class Wednesday, Apr. 30
- Important metrics
  - Contents of the presentation: 60%
    - Inclusion of all important points as mentioned in the report
    - The quality of the research and making the right points
  - Quality of the presentation itself: 15%
  - Presentation manner: 10%
  - Q&A handling: 10%
  - Staying in the allotted presentation time: 5%
  - Judging participation and sincerity: 5%

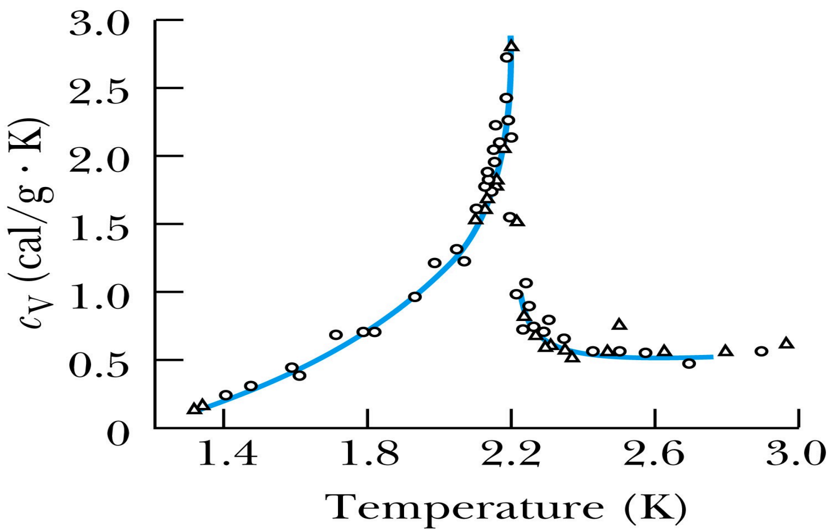
Liquid Helium

- Has the lowest boiling point of any element (4.2 K at 1 atmosphere pressure) and has no solid phase at normal pressure
- Helium is so light, has high speed and so escapes outside of the Earth atmosphere ➔ Must be captured from underground



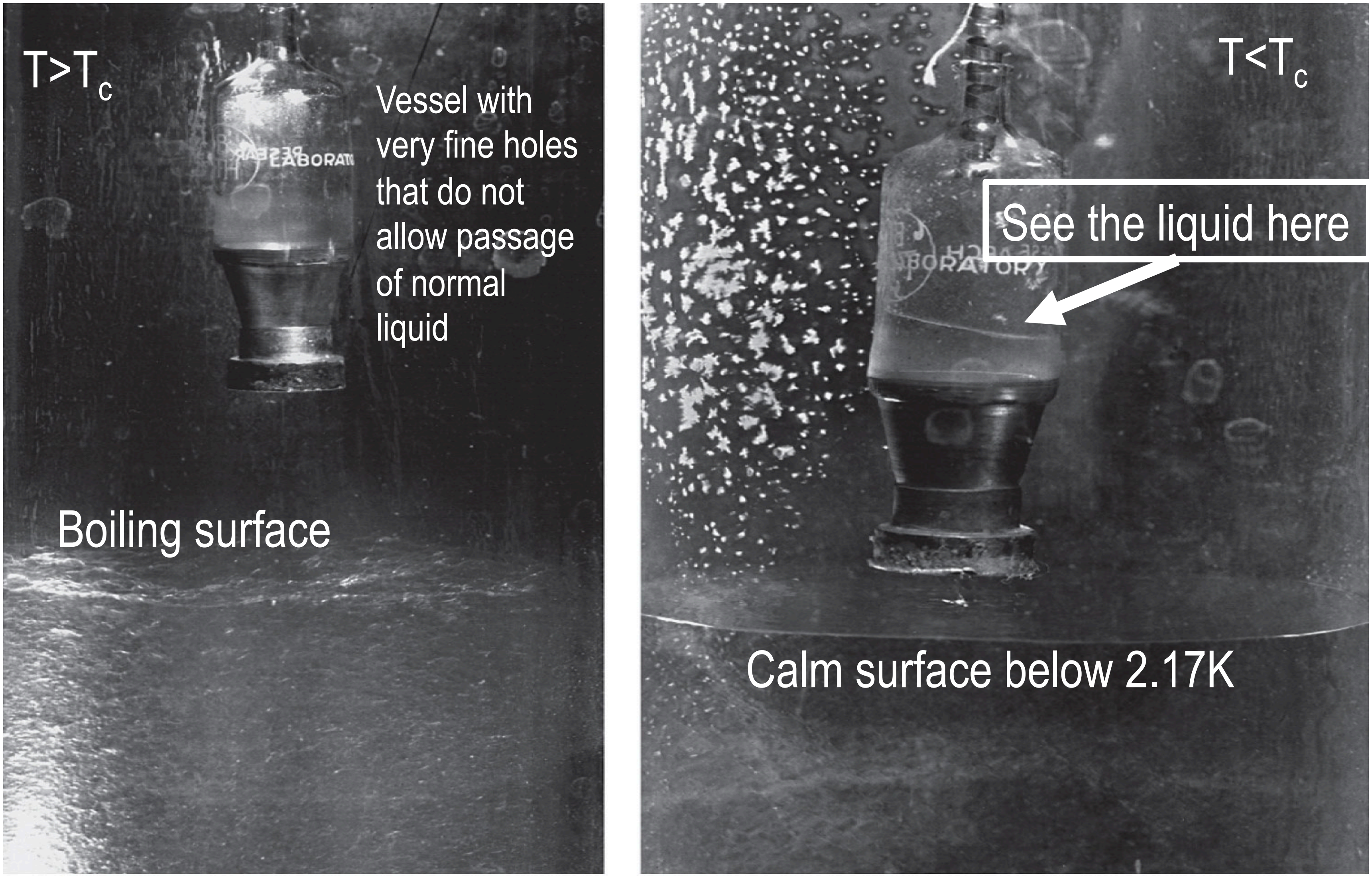
Liquid Helium

The specific heat of liquid helium as a function of temperature



- The temperature at about 2.17 K is referred to as the ***critical temperature (T_c), transition temperature*, or the *lambda point*.**
- As the temperature is reduced from 4.2 K toward the lambda point, the liquid boils vigorously. At 2.17 K the boiling suddenly stops.
- What happens at 2.17 K is a transition from the **normal phase** to the **superfluid phase**.

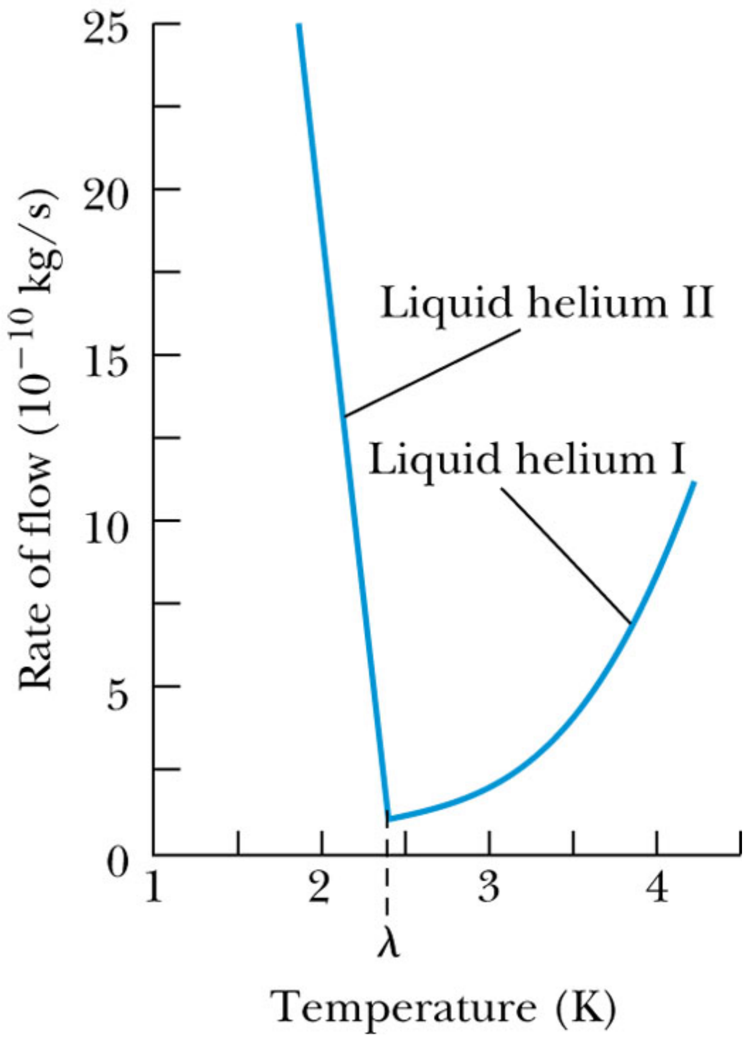
He Transition to Superfluid State



(a) (b)

Liquid Helium

- The rate of flow increases dramatically as the temperature is reduced because the superfluid has a low viscosity.
- **Creeping film** – formed when the viscosity is very low
- But when the viscosity is measured through the drag on a metal surface, He behaves like a normal fluid
  ➔ Contradiction!!



Liquid Helium

- Fritz London claimed (1938) that liquid helium below the lambda point is a mixture of superfluid and normal fluid.
  - As the temperature approaches absolute zero, the superfluid approaches 100% superfluid.
- The fraction of helium atoms in the superfluid state:

$$F = 1 - \left(\frac{T}{T_c}\right)^{3/2}$$

- Superfluid liquid helium (^{4}He) is referred to as a **Bose-Einstein condensation**.
  - ^{4}He is a boson thus it is not subject to the Pauli exclusion principle
  - all particles are in the same quantum state

Superconductivity

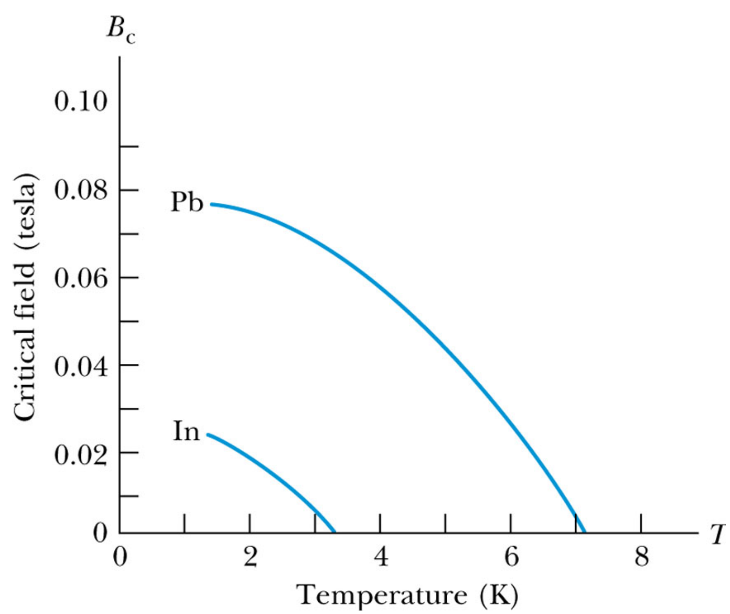
- Superconductivity is characterized by the absence of electrical resistance and the expulsion of magnetic flux from the superconductor and was discovered 100 yrs ago

It is characterized by two macroscopic features:

- **Zero resistivity**
  - First discovered in 1911 by Onnes who achieved temperatures approaching 1 K with liquid helium.
  - In a superconductor the resistivity drops abruptly to zero at the *critical* (or *transition*) *temperature* T_c.
  - Superconducting behavior tends to be similar within the given column of the periodic table.
  - In 1956 – 1958, British physicists led by S.C. Collins established a current in a superconducting ring without a power source

Superconductivity –Meissner Effect

- The complete expulsion of magnetic flux from within a superconductor by generating a screening current discovered in 1933 by W. Meissner and R. Oschenfeld
- The Meissner effect works only to the point where the **critical field** B_c is exceeded, and the superconductivity is lost until the magnetic field is reduced to below B_c.
- The critical field varies with temperature.



- To use a superconducting wire to carry current without resistance, there will be a limit (critical current) to the current that can be used.

Superconductivity – Zero Resistivity

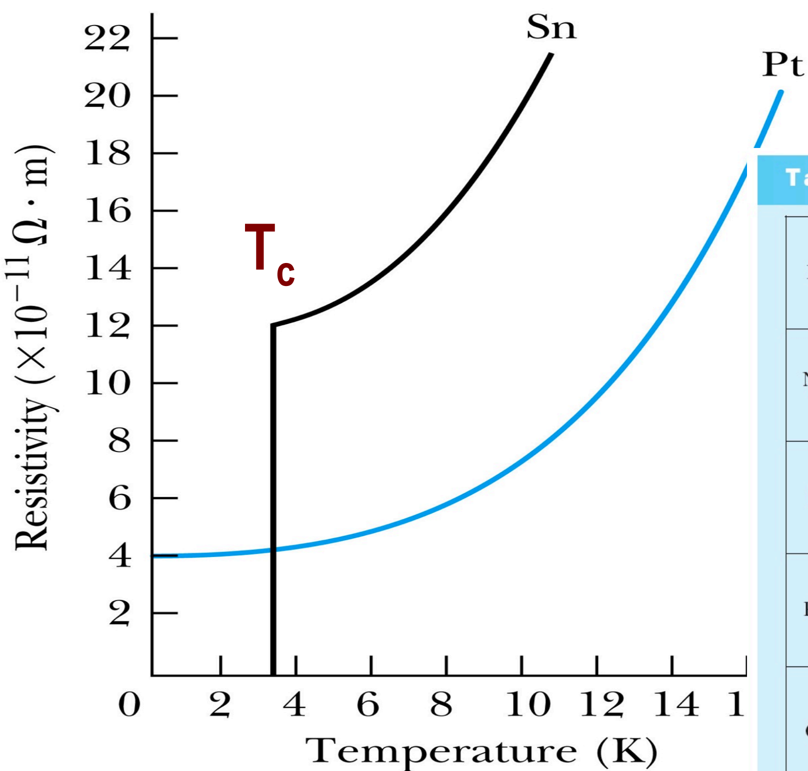


Table 10.5 Superconductivity Parameters of the Elements

Superconducting transition temperatures and critical fields

Upper number: Transition temperature in K
Lower number: Critical magnetic field at absolute zero in 10^{-4} tesla

Li	Be											B	C	N	O	F	Ne
Na	Mg											Al 1.18 105	Si	P	S	Cl	Ar
K	Ca	Sc	Ti 0.40 56	V 5.40 1408	Cr	Mn	Fe	Co	Ni	Cu	Zn 0.85 54	Ga 1.08 58	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr 0.61 47	Nb 9.25 2060	Mo 0.92 96	Tc 7.77 1410	Ru 0.49 69	Rh	Pd	Ag	Cd 0.52 28	In 3.4 282	Sn 3.72 505	Sb	Te	I	Xe
Cs	Ba	La 6.00 1046	Hf 0.13 13	Ta 4.47 829	W 0.02 1.15	Re 1.70 200	Os 0.66 70	Ir 0.11 16	Pt	Au	Hg 4.15 411	Tl 2.3 178	Pb 7.20 803	Bi	Po	At	Rn
Fr	Ra	Ac															

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu 0.1 350
Th 1.38 160	Pa 1.4	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

From B. W. Roberts, *Properties of Selected Superconductive Materials*, Supplement, NBS Technical Note 983, Washington, DC: U.S. Government Printing Office (1978).

Type I and Type II Superconductors

There is a lower critical field, B_{c1} and an upper critical field, B_{c2}.

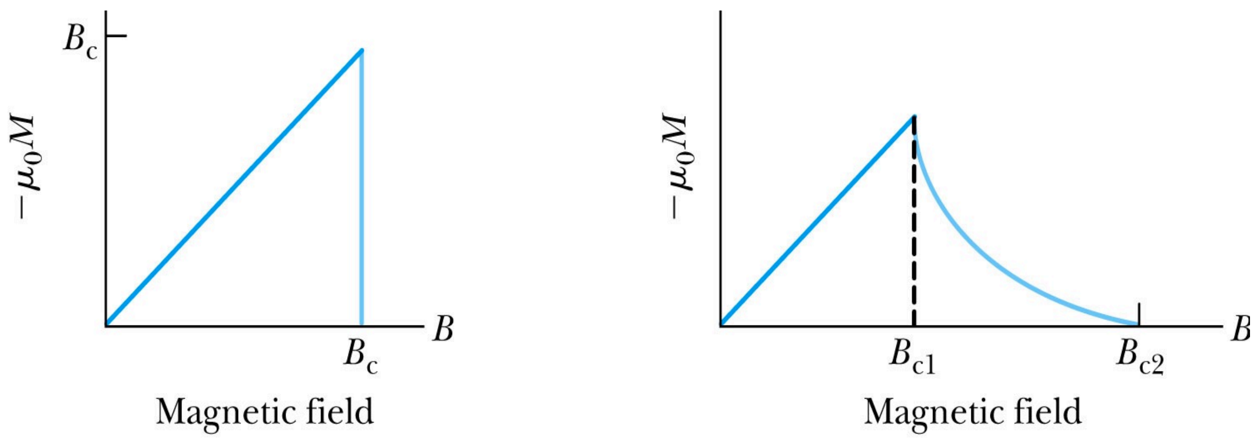
Type II: Below B_{c1} and above B_{c2}.

Behave in the same manner

Type I: Below and above B_c

Type I and Type II Superconductors

- Between B_{c1} and B_{c2} (vortex state), there is a partial penetration of magnetic flux although the zero resistivity is not lost.



(a) Type I (b) Type II

Lenz's law:

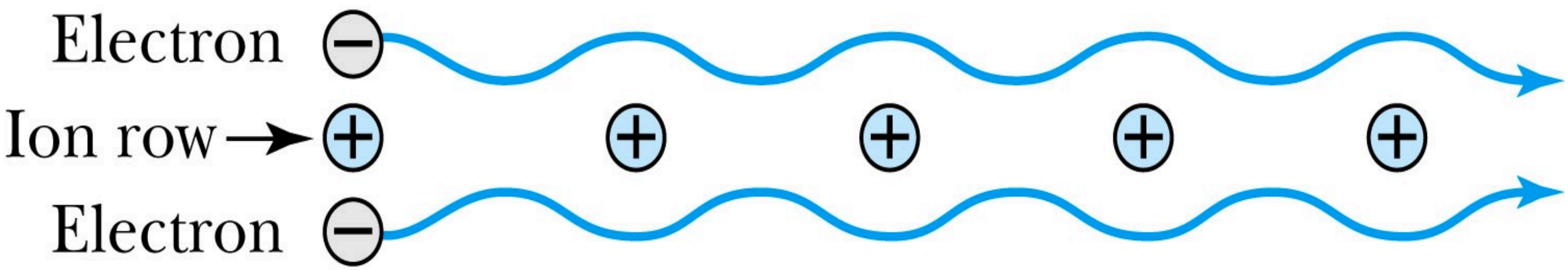
- A phenomenon from classical physics
- A changing magnetic flux generates a current in a conductor in such way that the current produced will oppose the change in the original magnetic flux.

Superconductivity

Bardeen-Cooper-Schrieffer theory (electron-phonon interaction):

1) Electrons form **Cooper pairs** which propagate throughout the lattice.
2) Propagation is without resistance because the electrons move in resonance with the lattice vibrations (**phonons**).

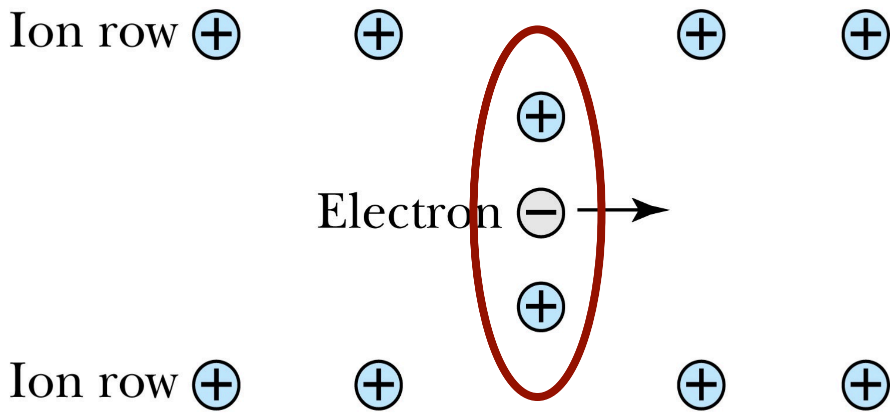
- How is it possible for two electrons to form a coherent pair?



- Each of the two electrons experiences a net attraction toward the nearest positive ion.
- Relatively stable electron pairs can be formed. The two fermions (spin ½ particles) combine to form a boson (integer spin). Then the collection of these bosons condense to form the superconducting state.

Superconductivity

- Considering just one of the two electrons, the propagation wave that is created by lattice deformation due to the Coulomb attraction between the electron and ions is associated with phonon transmission, and the electron-phonon resonance allows the electron to move without resistance.



- The complete BCS theory predicts other observed phenomena.
  1) An isotope effect with an exponent very close to 0.5 of mass. ($M^{0.5}T_c$=constant)
  2) It gives a critical field. $$B_c(T) = B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$
  3) Predicts that metals with higher resistivity in room temperature are better superconductors

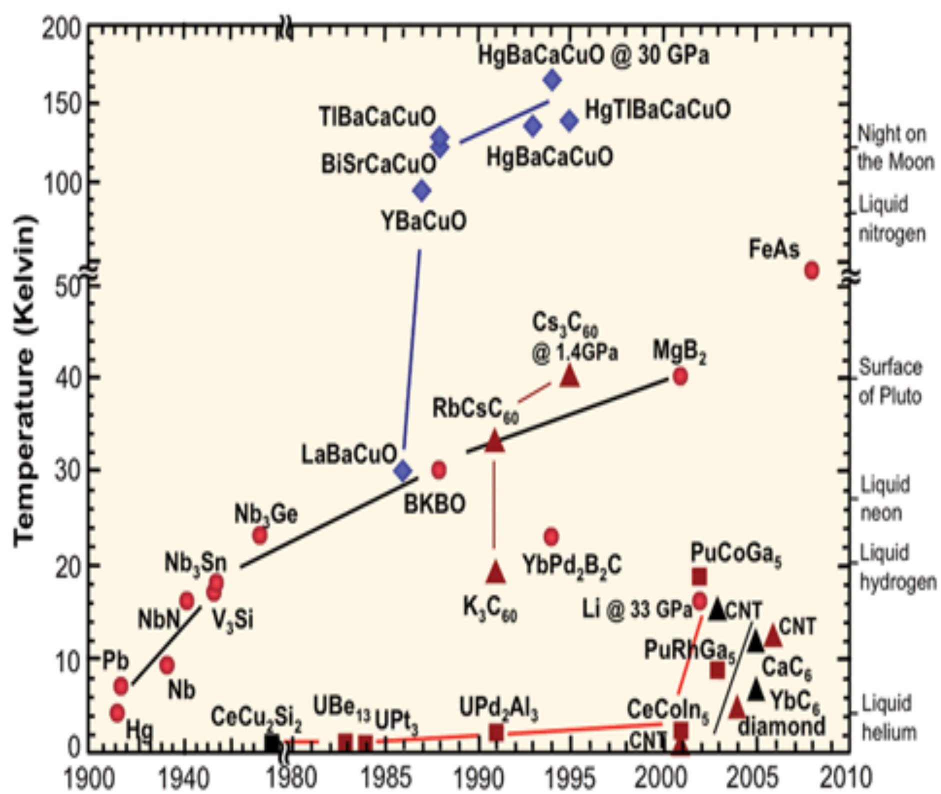
The Search for a Higher T_c

- Keeping materials at extremely low temperatures is very expensive and requires cumbersome insulation techniques.
- Making liquid He is very hard

Table 10.7 Superconductivity Records Through the Years

Material	Type	T_c (K)	Year of T_c Measurement
Hg	Element	4.2	1911
Pb	Element	7.2	1913
Nb	Element	9.3	1930
Nb_3Sn	Alloy	18.1	1954
$Nb_3(Al_{0.75}Ge_{0.25})$	Intermetallic	20–21	1966
Nb_3Ga	Intermetallic	20.3	1971
Nb_3Ge	Intermetallic	23.2	1973
$Ba_xLa_{5-x}Cu_5O_{5(3-y)}$	Ceramic	30–35	1986
$(La_{0.9}Ba_{0.1})_2CuO_{4-\delta}$ (at 1 GPa pressure)	Ceramic	52.5	1986
$YBa_2Cu_3O_7$	Ceramic	93	1987
BiSrCaCuO	Ceramic	105–120	1988
TlBaCaCuO	Ceramic	110–125	1993
$HgBa_2Ca_2Cu_4O_{1+x}$	Ceramic	134	1994
$HgBa_2Ca_2Cu_3O_{8+x}$ (at 30 GPa pressure)	Ceramic	164	1994

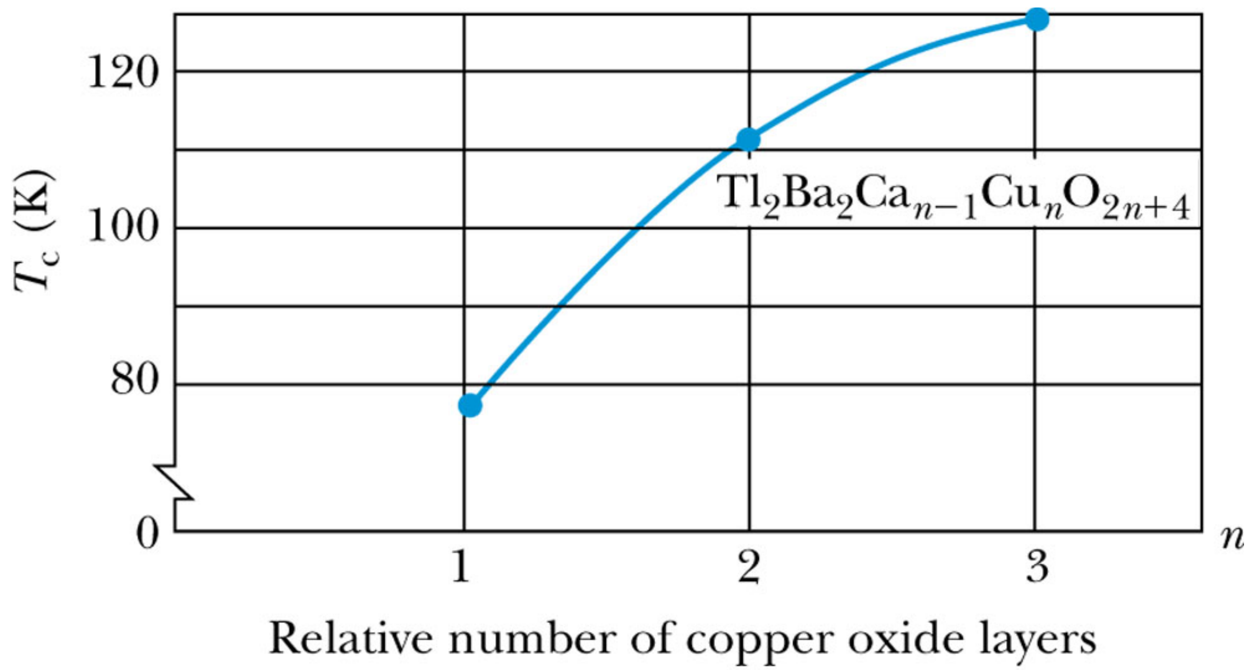
From C. P. Poole, Jr., T. Datta, and H. A. Farach, *Copper Oxide Superconductors*, New York: Wiley Interscience (1988), p. 7.



The Search for a Higher T_c

- The copper oxide superconductors fall into a category of **ceramics**.
- Most ceramic materials are not easy to mold into convenient shapes.
- There is a regular variation of T_c with n.

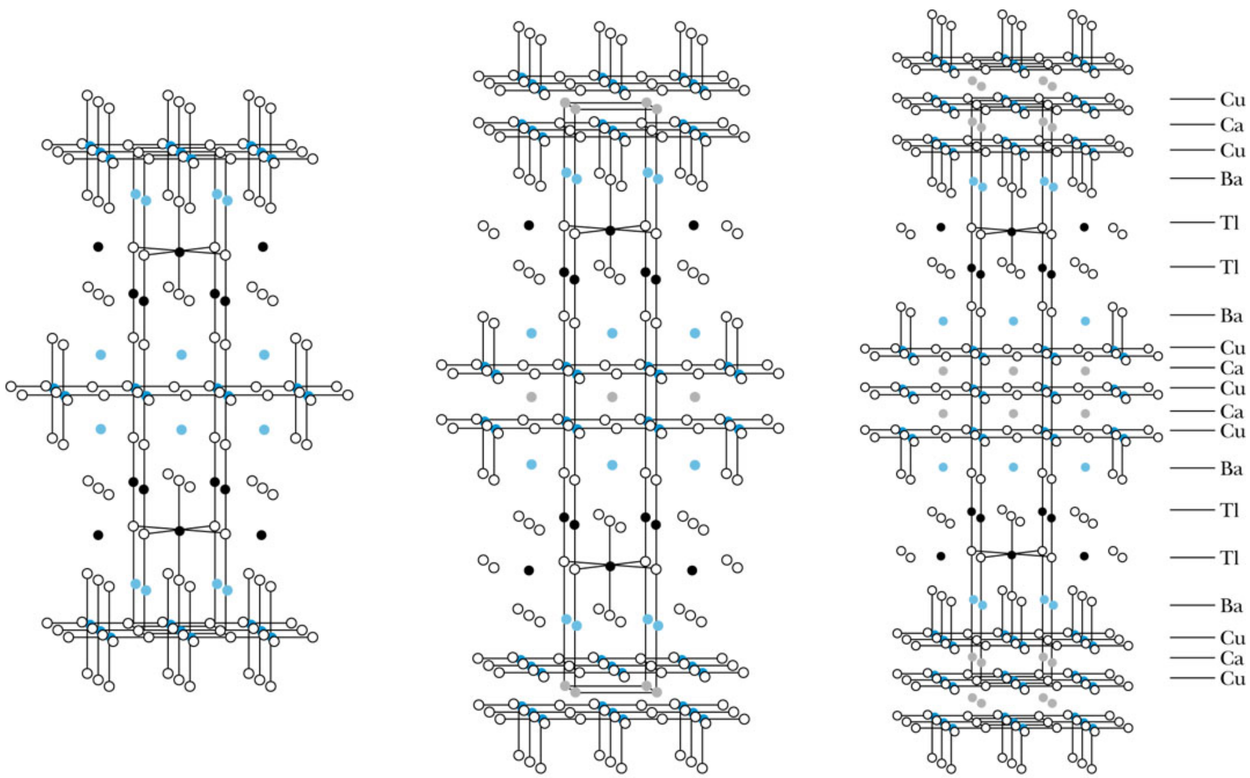
T_c of thallium-copper oxide with n = 3



The Search for a Higher T_c

- Higher values of *n* correspond to more stacked layers of copper and oxygen.

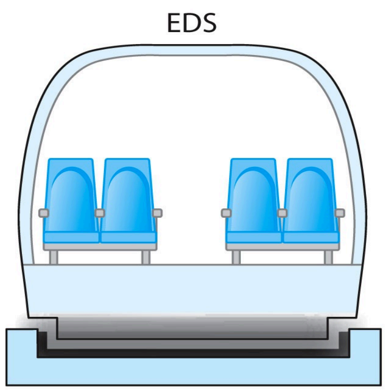
thallium-based superconductor



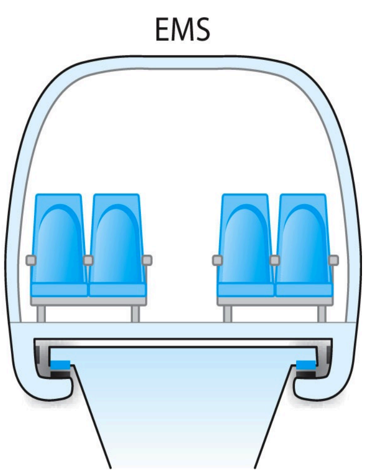
$Tl_2Ba_2CuO_6$ (a) $Tl_2Ba_2CaCu_2O_8$ (b) $Tl_2Ba_2Ca_2Cu_3O_{10}$ (c)

Applications of Superconductivity

Maglev: Magnetic levitation of trains



Electromagnets on the guideway levitate the car.



Electromagnets on the cars lift the cars.

- In an electro-dynamic system (EDS), magnets on the guide-way repel the car to lift it.
- In an electromagnetic system (EMS) , magnets attached to the bottom of the car lie below the guide-way and are attracted upward toward the guide-way to lift the car.

Generation and Transmission of Electricity

- Significant energy savings if the heavy iron cores used today could be replaced by lighter superconducting magnets.
- Expensive transformers would no longer have to be used to step up voltage for transmission and down again for use.
- Energy loss rate for transformers is

$$P_{lost} = I^2 R = P_{trans}^2 R / V^2$$

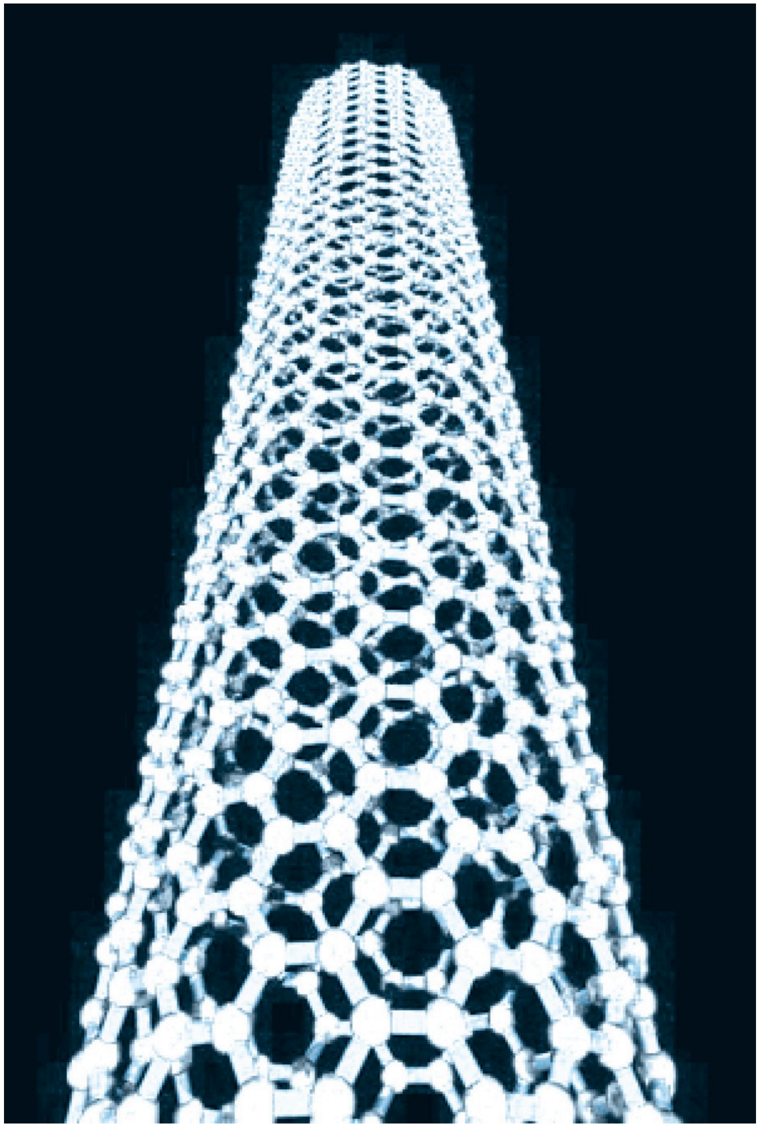
- **MRI** obtains clearer pictures of the body's soft tissues, allowing them to detect tumors and other disorders of the brain, muscles, organs, and connective tissues.

Nanotechnology & Carbon Nanotubes

- Nanotechnology is generally defined as the scientific study and manufacture of materials on a submicron scale.
- These scales range from single atoms on the order of 0.1 nm up to 1 micron (1000 nm).
- This technology has applications in engineering, chemistry, and the life sciences and, as such, is interdisciplinary.
- In 1991, following the discovery of C_{60} buckminsterfullerenes, or "buckyballs," Japanese physicist Sumio Iijima discovered a new geometric arrangement of pure carbon into large molecules.
- In this arrangement, known as a carbon nanotube, hexagonal arrays of carbon atoms lie along a cylindrical tube instead of a spherical ball.

Structure of a Carbon Nanotube

- There is virtually no limit to the length of the tube. *From Chris Ewels/www.ewels.info*
- leads to two types of nanotubes. A single-walled nanotube has just the single shell of hexagons as shown.
- In a multi-walled nanotube, multiple layers are nested like the rings in a tree trunk.
- Single-walled nanotubes tend to have fewer defects, and they are therefore stronger structurally but they are also more expensive and difficult to make.



Applications of Nanotubes

- Because of their strengths, they are used as structural reinforcements in the manufacture of composite materials
  - (batteries in cell-phones use nanotubes in this way)
- Nanotubes have very high electrical and thermal conductivities, and as such lead to high current densities in high-temperature superconductors.
- One problem in the development of truly small-scale electronic devices is that the connecting wires in any circuit need to be as small as possible, so that they do not overwhelm the nanoscale components they connect.
- In addition to the nanotubes already described, semiconductor wires (for example indium phosphide) have been fabricated with diameters as small as 5 nm.
- These **nanowires** have been shown useful in connecting nanoscale transistors and memory circuits. These are referred to as **nanotransistors**

Graphene

- A new material called **graphene** was first isolated in 2004. Graphene is a single layer of hexagonal carbon, essentially the way a single plane of atoms appears in common graphite.
- A. Geim and K. Novoselov received the 2010 Nobel Prize in Physics for "ground-breaking experiments." Pure graphene conducts electrons much faster than other materials at room temperature.
- Graphene transistors may one day result in faster computing.

Graphene

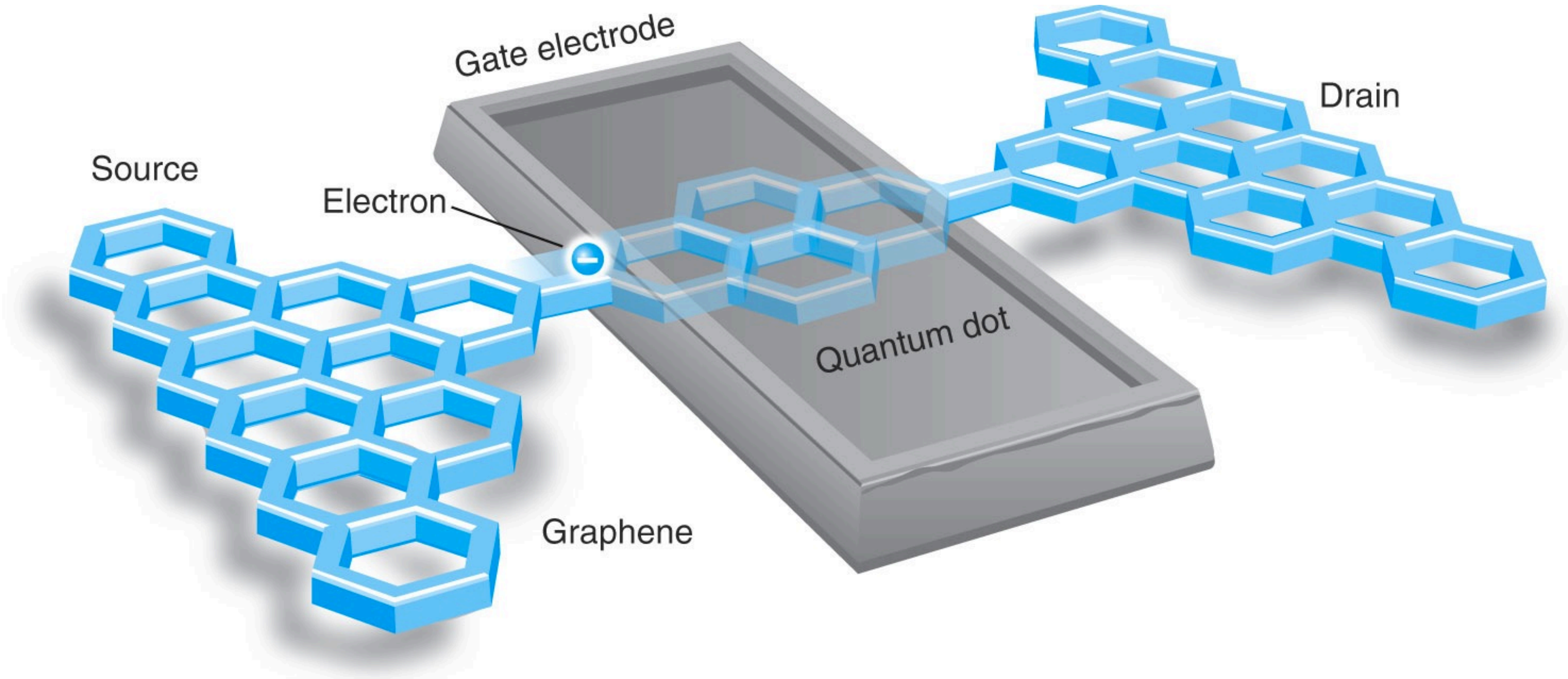


Figure 11.33 Schematic diagram of graphene-based transistor developed at the University of Manchester. The passage of a single electron from source to drain registers 1 bit of information—a 0 or 1 in binary code.

Quantum Dots

- Quantum dots are nanostructures made of semiconductor materials.
  - They are typically only a few nm across, containing up to 1000 atoms.
  - Each contains an electron-hole pair confined within the dot's boundaries, (somewhat analogous to a particle confined to a potential well discussed in Chapter 6.
- Properties result from the fact that the band gap varies over a wide range and can be controlled precisely by manipulating the quantum dot's size and shape.
  - They can be made with band gaps that are nearly continuous throughout the visible light range (1.8 to 3.1 eV) and beyond.

Nanotechnology and the Life Sciences

- The complex molecules needed for the variety of life on Earth are themselves examples of nanoscale design.
- Examples of unusual materials designed for specific purposes include the molecules that make up claws, feathers, and even tooth enamel.

Information Science

- It's possible that current photolithographic techniques for making computer chips could be extended into the hard-UV or soft x-ray range, with wavelengths on the order of 1 nm, to fabricate silicon-based chips on that scale
- In the 1990s physicists learned that it is possible to take advantage of quantum effects to store and process information more efficiently than a traditional computer. To date, such quantum computers have been built in prototype but not mass-produced.