IISc Bangalore

UP201 – Introductory Physics III

An Invitation to Physics

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August 2, 2017

Overview of First Meeting

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- What is this course about?

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- Why you should do this course?

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- Logistics
- ...
- ...time permitting : A Metallic Story!
- ...interspersed by **Your questions**!...

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- ...time permitting : A Metallic Story!
- ...interspersed by **Your questions**!...and my questions...

Lets Physics[1]...

[1] Physics as a *verb*!

What is Physics[2]?

[2] Physics as a *noun*

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- *Nature:* What we "see" around us
- *Order:* There seems to be something "regular" going on (e.g. Sun rises in the east, ...or you feel hungry every four hours!)

[2] Physics as a *noun*

What do we “see”?

- We sense space and time!

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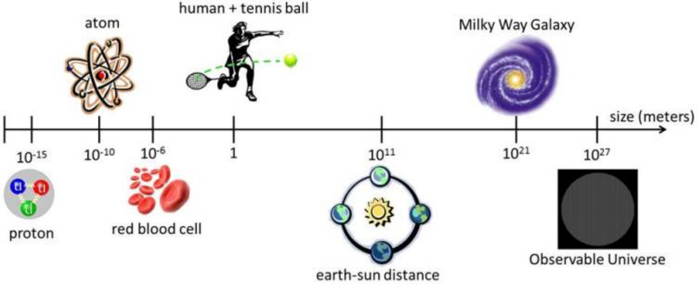

(Source: Internet)

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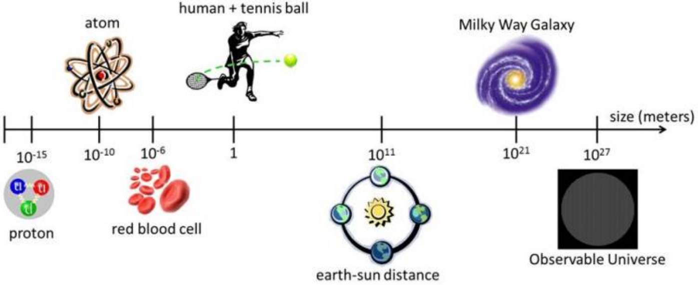

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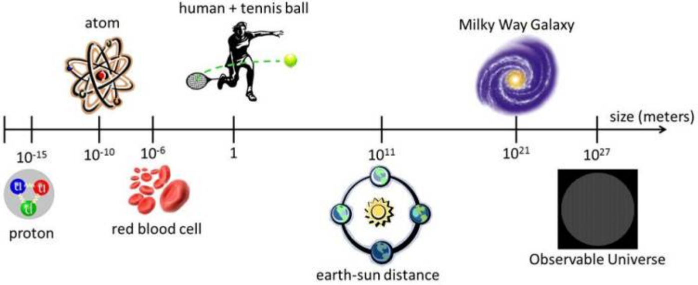

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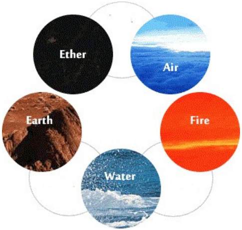
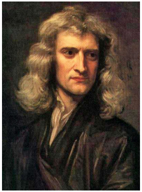
- We have probed ("seen") an astonishing amount of things from the smallest (sub-nuclear) to the largest (on the scale of the universe)
- Timescales range from 10^{-23} seconds to 14×10^9 years!

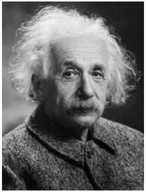
The Quest

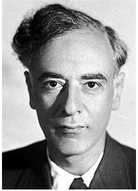
- How to make sense of what we sense?
- Ancient wisdom...



- ...to work of more recent stalwarts...





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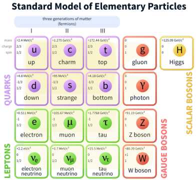
- Roughly, Nature is described by quantum mechanics on the smallest scales... and by general theory of relativity at the largest scales
- The universe had a beginning (about 13.5 billon years ago!)...and is expanding
- “Things” made of Leptons, Quarks, Force carrying bosons, Higgs boson...the standard model



(Wikipedia)

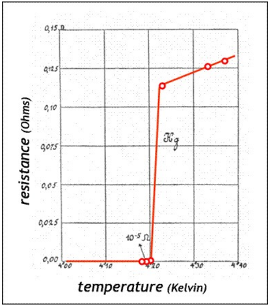
- Our planet Earth itself formed about 3.5 billon years back...Life on earth arose from self replicating chemicals...to dinosaurs...to apes...to us!
- ...
- ...and yet we do not know so many things! Like what?

Physics Organization...

- Study of physics is organized into several interrelated areas...(not surprisingly, by scales!!)
- $< 10^{-12}m$: High Energy Physics
- Between 10^{-12} and $10^{6}m$: Condensed Matter Physics
- $> 10^{6}m$: Astronomy and Astrophysics
- Such divisions are due to human limitations...there is only a unified subject...natural philosophy or physics!

A Challenge

- Superconductivity
(discovered in 1911 by Kammerling Onnes)...a zero resistance state!



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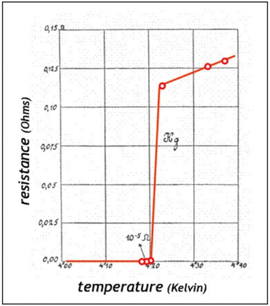

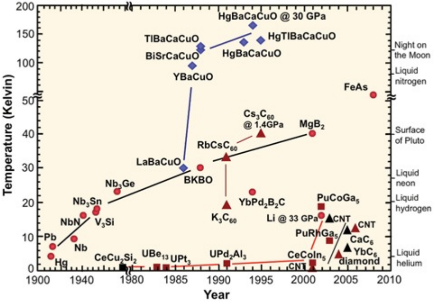

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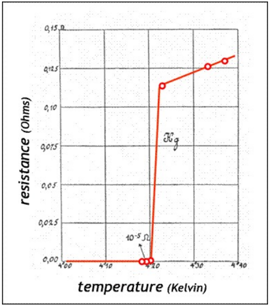

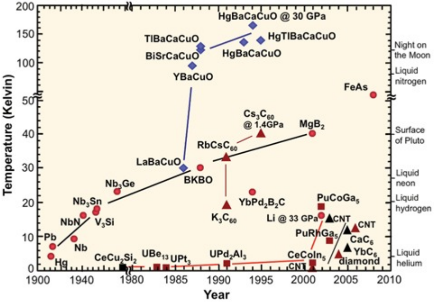

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- **Challenge: Can you make a room temperature superconductor?** **If you do so, things will change for ever; many new things like quantum computers will become a reality!**

More Challenges...An Invitation to Physics

Many unanswered questions:

- High Energy Physics: How to marry quantum mechanics and general relativity?
- Astronomy and Astrophysics: Dark matter, Dark energy...
- Condensed Matter Physics: How do many degrees of freedom organize themselves? For example, how does the human (or for that matter of any higher organism) work?

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(Source: Internet)

- **What is YOUR question/challenge?**

Why should you do this (or any) course?

- An important aspect of education/training
  - In any "research" activity: **You have to known when you should be surprised! How do you know you have made a discovery?**
  - This requires some knowledge of the subject area that will enable you to
    - ★ Understand open questions
    - ★ Formulate new open questions
    - ★ Find answers to questions posed by others or you
- Knowledge
  - **Conceptual:** Focussing on conceptual ideas of the field
  - **Technical:** Tools and techniques need to explore/formulate/explain ideas

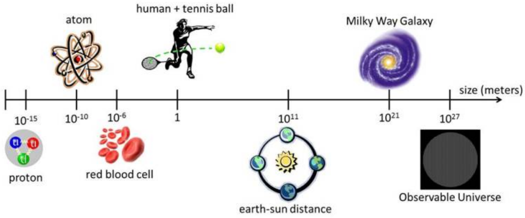
  An example: The physics concept of "broken symmetry" is useful in describing phases of matter. Group theory is the technical stuff behind this...
- **The aim of this course is to lay conceptual foundations of physics...for you to be able to appreciate the open problems..and even prepare to tackle some of them..**

Introductory Physics @IISc

- UP101 – Focusing on mechanics
- UP102 – Focusing on electromagnetism
  UP101/UP102 combined deals with "Classical Physics"
- UP201 – Thermal and Modern Physics (everything we discuss was discovered after 1850)
  Syllabus:
  - Temperature, The First Law of Thermodynamics, Kinetic Theory of Gases and Maxwell -Boltzmann Statistics, Heat Engines, Entropy and the Second Law of Thermodynamics
  - Relativity
  - Introduction to Quantum Physics, Basics of Quantum Mechanics
  - Atomic , Molecular and Solid state Physics,
  - Nuclear Physics, Particle Physics
  - Cosmology

More about UP201...Nature of Physics Theories

- Physics theories can be classified[3] as
  - **Microscopic theories**
    - ★ Questions like: What are the laws of nature?
    - ★ What are things made of?
  - **Phenomenological theories**
    - ★ How to describe things on a given scale (without necessarily asking questions about lower scales)?
- Note/Caution: One persons microscopics may be another's phenomenology



(Source: Internet)

[3] As you grow older you will find this to be entirely superfluous

More about UP201...

From a “terrestrial human” perspective stuff is UP201 can be basketed as

- **Microscopic theories**
  - Relativity
  - Introduction to Quantum Physics, Basics of Quantum Mechanics
  - Atomic , Molecular and Solid state Physics,
  - Nuclear Physics, Particle Physics (really, these are also phenomenological!)
- **Phenomenological theories**
  - Temperature, The First Law of Thermodynamics, Kinetic Theory of Gases and Maxwell -Boltzmann Statistics, Heat Engines, Entropy and the Second Law of Thermodynamics
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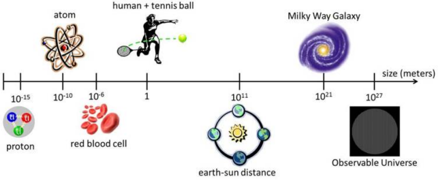

(Source: Internet)

Why should you do this course?

- To familiarize yourself about what is known in physics
- To pick up **physics concepts**, this course will *not* technique heavy (math prerequisites have all been covered in earlier courses)
- ...
- ...so as to appreciate the open questions...and make new ones yourself!
- ...and eventually to physics[4]!
- Goal: **To know when to be surprised**

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[4] as a verb

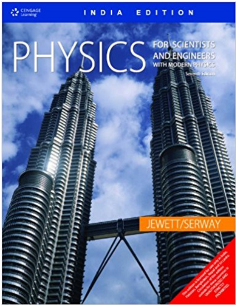
Logistics

Useful Info About the Course

1. **Venue:** F-12 1st Floor UG Building II (Old Physics Building)
2. **Time:** Lectures – Monday and Wednesday 11:00AM $\rightarrow$ 12:00noon, Tutorial – Friday 11:00AM $\rightarrow$ 12:00noon
3. **Lab:** Already announced (details will be discussed by Lab Instructors)
4. **Homeworks:** Weekly about 5-10 problems. Will not be collected, but some exam questions will be based on homeworks
5. **Exams:** (one or two) Mid-sem exams (50% weight) and (50% weight) for end semester exam
6. **Instructor Office Hours:** Right after class from 12:00 $\rightarrow$ 12:30
7. **Teaching Assistants:** To be announced

Textbook

- We will (roughly) follow Serwey and Jewett

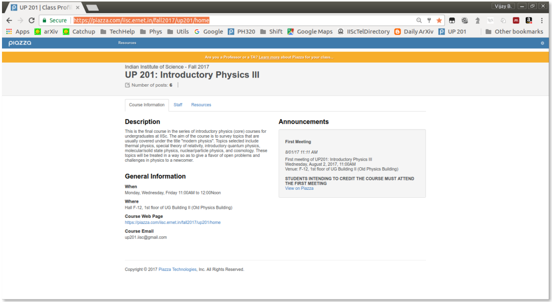


(Rs. 595 at amazon.in)

- Other reading material will be indicated in class from time to time
- Related useful references
    - Young and Friedman, University Physics (12th Edition)
    - Halliday, Resnick and Walker, Fundamentals of Physics, Extended (8th Edition)
    - Harris Benson , University Physics, Revised Edition
    - Kenneth Krane, Modern Physics, Second Edition

Webpage

- Course web page
  https://piazza.com/iisc.ernet.in/fall2017/up201/home



- Students crediting the course **MUST** enroll on the webpage (need ug.iisc.in email address)
- All communication from the instructor including homeworks, announcements etc. will be through the webpage only
- Course email : **up201.iisc@gmail.com** – all communication about the course must use this email address; instructor/TA personal emails must be avoided

A Metallic Story

What is Metallic about a Metal?

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- Copper is a metal, gold is also...so is sodium...they look so different, and yet we insist that “they are the same”!

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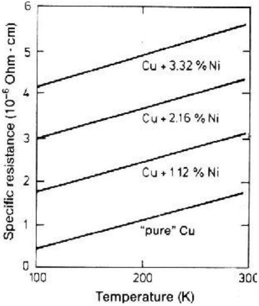
- Resistivity of metals increases with temperature...



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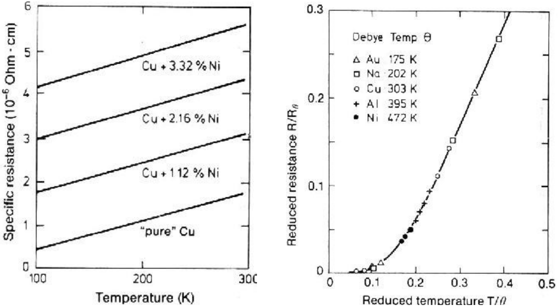

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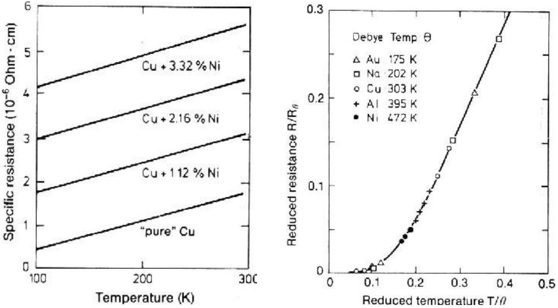

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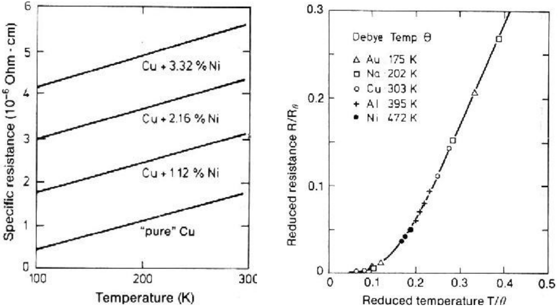

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- Despite their different appearance, there is something deeply common among various metals...this commonality characterizes the "metallic state"
- ...Drudé theory of metals

Some Experimental Facts Regarding Metals

- Dulong-Petit Law

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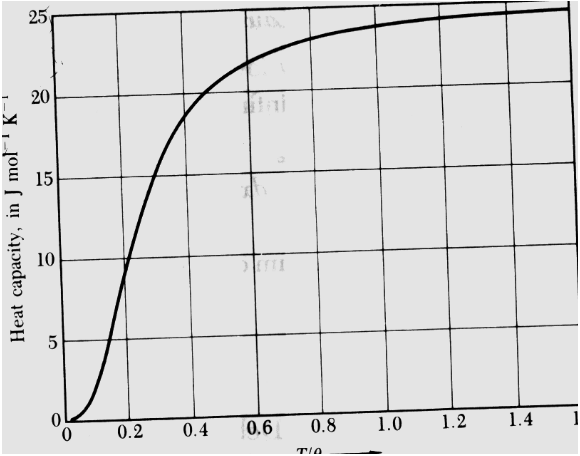

(Kittel)

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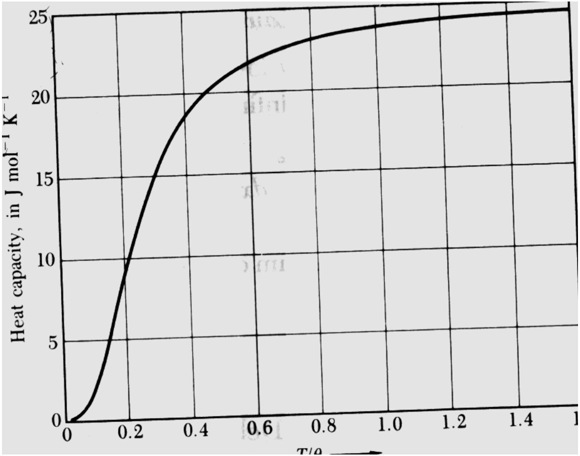

(Kittel)

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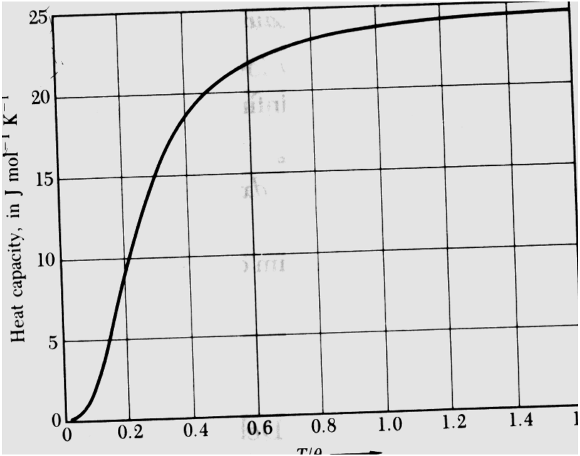

(Kittel)

- High-Temperature Molar Specific Heat = $3R$
- Atoms - Classical Oscillators

Some Experimental Facts Regarding Metals

- Wiedemann-Franz Law: Ratio of thermal (κ) to electrical conductivities (σ) depends linearly on T
  $\kappa/\sigma = (Const)T, \qquad (Const) \approx 2.3 \times 10^{-8}\text{watt-ohm/K}^2$

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EXPERIMENTAL THERMAL CONDUCTIVITIES AND LORENZ NUMBERS OF SELECTED METALS

ELEMENT	273 K		373 K	
	κ (watt/cm-K)	$\kappa/\sigma T$ (watt-ohm/K^2)	κ (watt/cm-K)	$\kappa/\sigma T$ (watt-ohm/K^2)
Li	0.71	2.22×10^{-8}	0.73	2.43×10^{-8}
Na	1.38	2.12		
K	1.0	2.23		
Rb	0.6	2.42		
Cu	3.85	2.20	3.82	2.29
Ag	4.18	2.31	4.17	2.38
Au	3.1	2.32	3.1	2.36
Be	2.3	2.36	1.7	2.42
Mg	1.5	2.14	1.5	2.25
Nb	0.52	2.90	0.54	2.78
Fe	0.80	2.61	0.73	2.88
Zn	1.13	2.28	1.1	2.30
Cd	1.0	2.49	1.0	
Al	2.38	2.14	2.30	2.19
In	0.88	2.58	0.80	2.60
Tl	0.5	2.75	0.45	2.75
Sn	0.64	2.48	0.60	2.54
Pb	0.38	2.64	0.35	2.53
Bi	0.09	3.53	0.08	3.35
Sb	0.18	2.57	0.17	2.69

(Ashcroft-Mermin)

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- Force on a charged particle (q), ($q = -e$ for electron, $\boldsymbol{E}, \boldsymbol{B}$–electric and magnetic fields)

$$\boldsymbol{F} = q(\boldsymbol{E} + \frac{\boldsymbol{p}}{m} \times \boldsymbol{B})$$

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- Current density $\boldsymbol{j} = -en\frac{\boldsymbol{p}}{m}$
- Conductivities:

$$\boldsymbol{j} = \sigma \boldsymbol{E} \ \text{(Electrical)}, \qquad \boldsymbol{q} \ = \ -\kappa \boldsymbol{\nabla} T \ \text{(Thermal)}$$

Drudé Theory

- Early 19^{th} century

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- Electrons treated as classical particles
- Electrons collide with atoms (and other electrons)
- About 10^{23} electrons (How to do this???)
- What would you do?

Drudé Model

- How to handle all the electrons?

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- Drudé Equation

$$\boldsymbol{p}(t+\mathrm{d}t) = \underbrace{\left(1-\frac{dt}{\tau}\right)}_{\text{prob. no coll.}} \left(\boldsymbol{p}(t)+\boldsymbol{F}\mathrm{d}t\right)$$

$$\Longrightarrow \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = -\frac{\boldsymbol{p}}{\tau}+\boldsymbol{F}$$

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- Drudé Equation gives drift velocity:

$$\begin{aligned} \boldsymbol{p}_d &= \tau \boldsymbol{F} \\ \Longrightarrow \boldsymbol{v}_d &= \frac{\tau}{m}\boldsymbol{F} \quad \text{(drift velocity)} \end{aligned}$$

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- Current density

$$\boldsymbol{j} = -ne\boldsymbol{v}_d = \frac{ne^2\tau}{m}\boldsymbol{E}$$

- Electrical conductivity

$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

So What?

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- How to calculate τ?
- Well, we don't know yet!
- And...so, what?
- Calculate relaxation times from conductivity measurements
- What do you think it will be?

Relaxation Times

- Calculated relaxation times

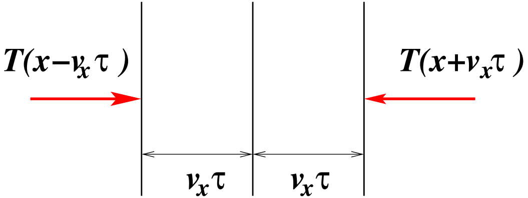
DRUDE RELAXATION TIMES IN UNITS OF 10^{-14} SECOND[a]

ELEMENT	77 K	273 K	373 K
Li	7.3	0.88	0.61
Na	17	3.2	
K	18	4.1	
Rb	14	2.8	
Cs	8.6	2.1	
Cu	21	2.7	1.9
Ag	20	4.0	2.8
Au	12	3.0	2.1
Be		0.51	0.27
Mg	6.7	1.1	0.74
Ca		2.2	1.5
Sr	1.4	0.44	
Ba	0.66	0.19	
Nb	2.1	0.42	0.33
Fe	3.2	0.24	0.14
Zn	2.4	0.49	0.34
Cd	2.4	0.56	
Hg	0.71		
Al	6.5	0.80	0.55
Ga	0.84	0.17	
In	1.7	0.38	0.25
Tl	0.91	0.22	0.15
Sn	1.1	0.23	0.15
Pb	0.57	0.14	0.099
Bi	0.072	0.023	0.016
Sb	0.27	0.055	0.036

(Ashcroft-Mermin)

Thermal Conductivity

- Energy of an electron at temperature T, $E[T] = \frac{3}{2}k_B T$



- A (one-D) body with a temperature gradient
- Magnitude of velocity (speed) in x direction = v_x
- Heat flux from left to right $= \dfrac{n}{2} v_x E[T(x - v_x\tau)]$
- Heat flux from right to left $= \dfrac{n}{2} v_x E[T(x + v_x\tau)]$

Thermal Conductivity contd.

- Net heat flux towards positive x axis

$$\begin{aligned} \boldsymbol{q} &= \frac{n}{2} v_x \left(E[T(x - v_x\tau)] - E[T(x + v_x\tau)] \right) = n v_x \frac{\partial E}{\partial T} \left(-\frac{\partial T}{\partial x} v_x \tau \right) \\ &= -n \underbrace{v_x^2}_{\frac{k_B T}{m}} \underbrace{\frac{\partial E}{\partial T}}_{\frac{3}{2}k_B} \frac{\partial T}{\partial x} = -\left(\frac{3nk_B^2 \tau T}{2m} \right) \frac{\partial T}{\partial x} \end{aligned}$$

- Thermal conductivity:

$$\boxed{\kappa = \frac{3nk_B^2 T\tau}{2m}}$$

And now, Wiedemann-Franz!

- Ratio of thermal to electrical conductivity

$$\frac{\kappa}{\sigma} = \frac{3}{2}\left(\frac{k_B}{e}\right)^2 T$$

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- Expt. value $\approx 2.3 \times 10^{-8}$watt-ohm/K^2! Celebrations!

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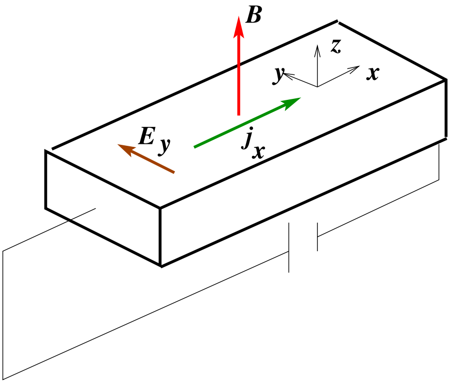
- Ok, turn the music down!

Hall Effect



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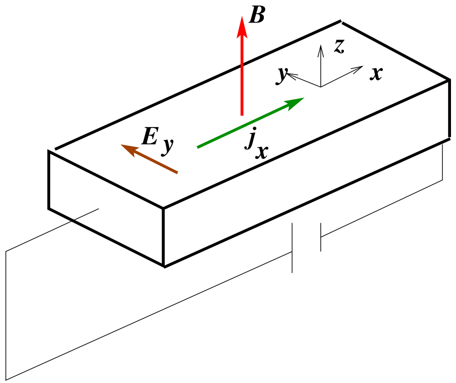

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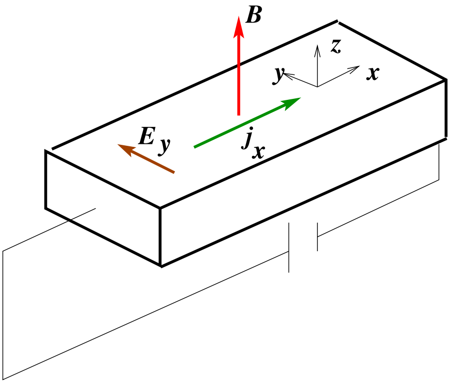

- Electric field applied in the x direction – current flows j_x
- Magnetic field B applied in the z direction
- An electric field E_y *develops* in the y-direction

Hall Effect contd.

- Hall coefficient

$$R_H = \frac{E_y}{j_x B}$$

- Drudé value of Hall coefficient

$$R_H^D = -\frac{1}{ne}$$

  (prove this!)
- Independent of relaxation time!

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HALL COEFFICIENTS OF SELECTED ELEMENTS IN MODERATE TO HIGH FIELDS[a]

METAL	VALENCE	$-1/R_H ne$
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Na	1	1.2
K	1	1.1
Rb	1	1.0
Cs	1	0.9
Cu	1	1.5
Ag	1	1.3
Au	1	1.5
Be	2	−0.2
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- *Stop the party!*

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