Spintronics and Nanomagnetics

ECS 521/641

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ECS 521/641

Credits: 4

Prerequisite/Desirable:

- Differential Equations, Matrix Algebra, MATLAB;
  Recommended:
  - Quantum Mechanics, Statistical Mechanics, Thermodynamics.

Learning Objectives:

- The objective of this course is to make students familiar with the basic and applied concepts behind information processing using electron's spin degree of freedom. Also, functional spin devices using emerging materials and phenomena will be discussed.

ECS 521/641: Course contents

Spintronics is an emerging field of basic and applied research in Physics and Engineering that exploits electron's spin degree of freedom for classical and quantum information processing. There has been enormous progress in the field of spintronics and nanomagnetics in recent years with the discovery of many new materials and phenomena. In fact, apart from magnetic hard drives we have, industries are manufacturing new sets of non-volatile spintronic memories, however, research on spintronic logic is still under way. The topics for this course include concept of spin, quantum mechanics and historical perspective of spin, Pauli spin matrices, Bloch sphere, spin-orbit interaction, Rashba and Dresselhaus interaction, spin relaxation, information processing with spin, Landau-Lifshitz-Gilbert (LLG) equation of magnetization dynamics, ferromagnetic resonance, spin waves, multiferroics and magneto-electric coupling, spin transfer torque, spin pumping, spin valves, magnetic tunnel junctions, spin Hall effect, topological insulators, spin-circuits.

ECS 521/641: Slides/Class notes

Selected Readings:

- Due to the emerging and interdisciplinary nature of the course, dedicated chapter-wise class notes will be provided.

Papers:

- K. Roy, "Spintronics: Recent developments on ultra-low-energy, area-efficient, and fast spin-devices and spin-circuits," TechConnect World Innovation, Nanotech 2017, Washington DC, 5, 51-54, 2017.
- K. Roy, "Ultra-low-energy Electric field-induced Magnetization switching in Multiferroic Heterostructures," SPIN, World Scientific (invited) 6, 1630001 (1-34), 2016.
- A. Fert, “The Origin, Development and Future of Spintronics,” Nobel Lecture in Physics, 2007.
- P. Grunberg, “From Spinwaves to Giant Magnetoresistance (GMR) and Beyond,” Nobel Lecture in Physics, 2007.

ECS 521/641: Grading

Grading

Homeworks:	30%
Mid-term Exam:	30%
Final Exam:	40%
Paper presentation?	

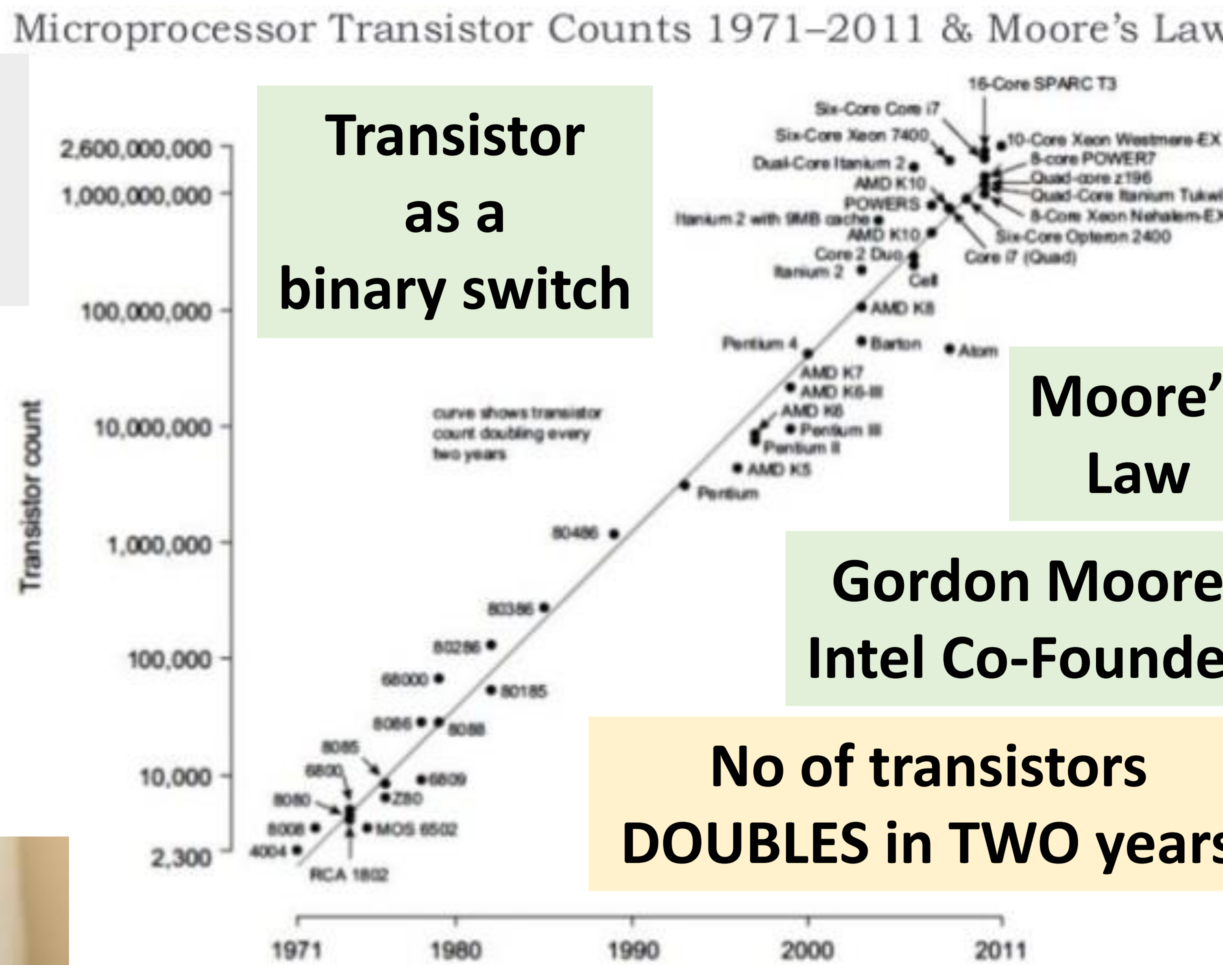
Questions/Comments/Suggestions

Send email for appointment, Email: kuntal@iiserb.ac.in, Room No. 302, Infinity/Academic Building – 1

Introduction and overview

Electronics: Development and future

Issues
- **Energy dissipation**
- **Process variation**



Transistor as a binary switch

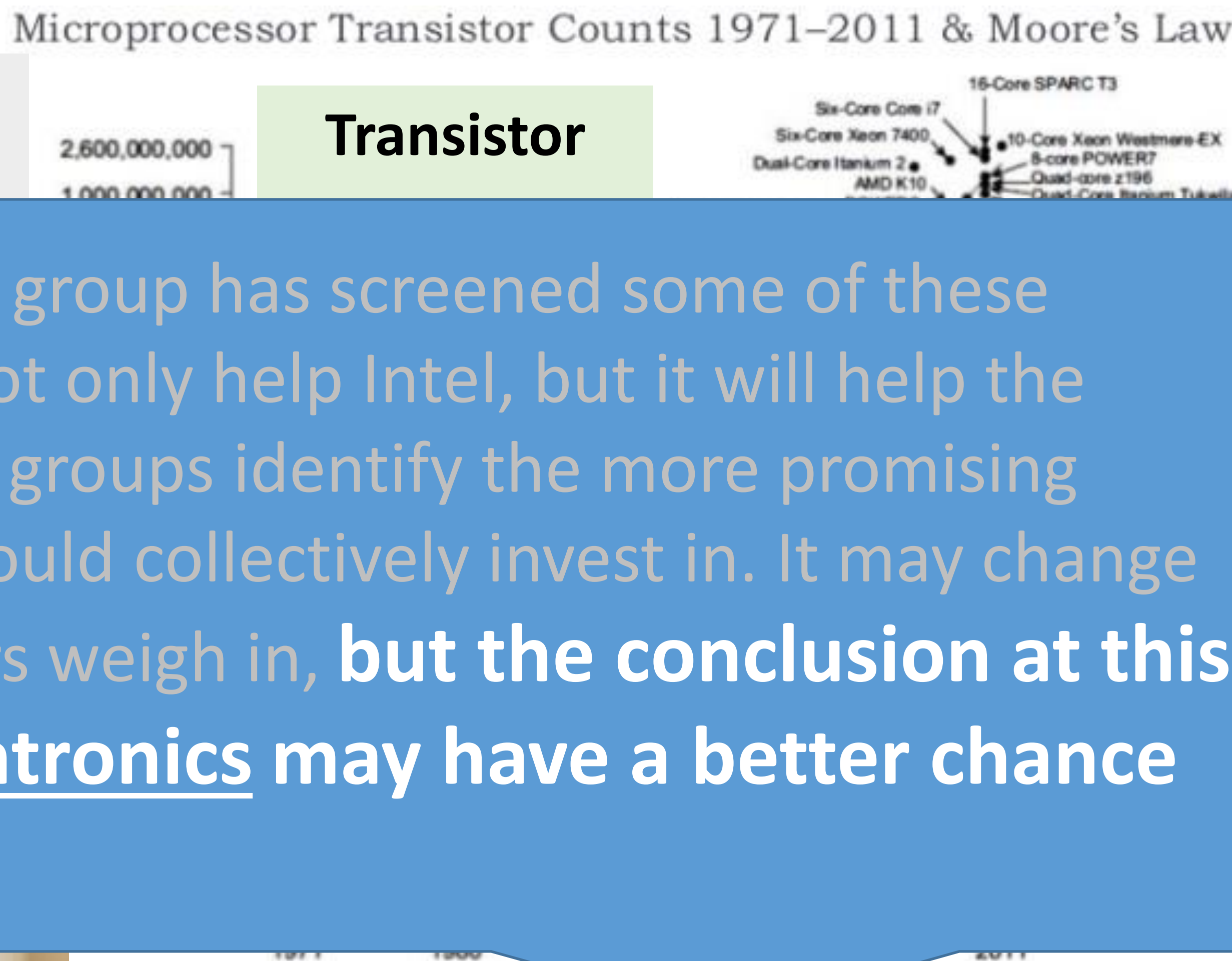
Moore's Law

Gordon Moore
Intel Co-Founder

No of transistors DOUBLES in TWO years

Intel, 14nm tech, 2016
Xeon (22 core), 7.2 billion

Electronics: Development and future



Transistor

Issues

➢ **Energy dissipation**

Bohr: Our research group has screened some of these options. This will not only help Intel, but it will help the university research groups identify the more promising options that we should collectively invest in. It may change as more researchers weigh in, **but the conclusion at this point is that <u>spintronics</u> may have a better chance in the future.**

Mark Bohr, a senior fellow at Intel

http://semiengineering.com/one-on-one-mark-bohr/ *(2014)*

Spintronic memory

From 2016 **www.mram-info.com**

[Everspin to demonstrate the world's fastest SSD based on its ST-MRAM]

[Everspin starts shipping perpendicular-MTJ based ST-MRAM chip samples]

[IBM demonstrated 11nm STT-MRAM junction, says "time for STT-MRAM is now"]

[IBM demonstrates Everspin's ST-MRAM in its ConTutto platform in a Power8 system]

[Samsung Foundry to start offering STT-MRAM by 2019]

[Samsung demonstrates a 8Mb embedded pMTJ STT-MRAM device]

[Aupera Technologies launches the world's first storage module based on Everspin's pMTJ STT-MRAM]

[Cobham's MRAM chips to reach Mars soon]

[Spin Transfer Technologies fabricated 20nm OST-MRAM MTJs, preparing to deliver samples]

[Spin Transfer Technologies produced working 60-nm STT-MRAM prototypes]

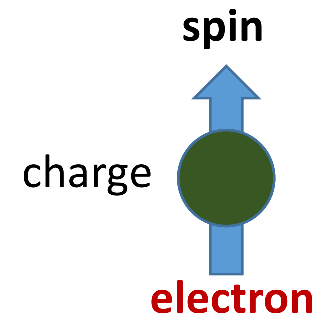
[Global Foundries to offer Everspin's PMTJ STT-MRAM as an embedded memory solution]

[IMEC researchers demonstrate the world's smallest pMTJ at 8nm]

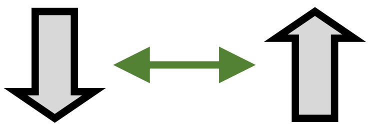
[Toshiba and Hynix prototype a 4 Gb STT-MRAM]

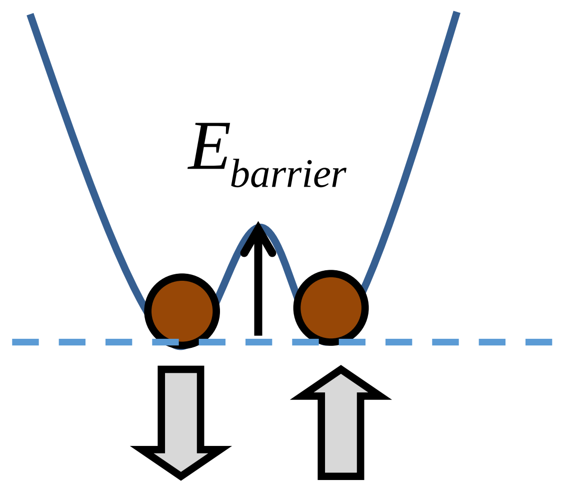
Spintronics: Spin-electronics

- Apart from having charge, an electron has **spin**



- Up/Down → 0/1 (binary information)
- **A rapidly developing nanotechnology**
  - Store, **non-volatile**
  - Process
  - Communicate
  - **In-built functionality**



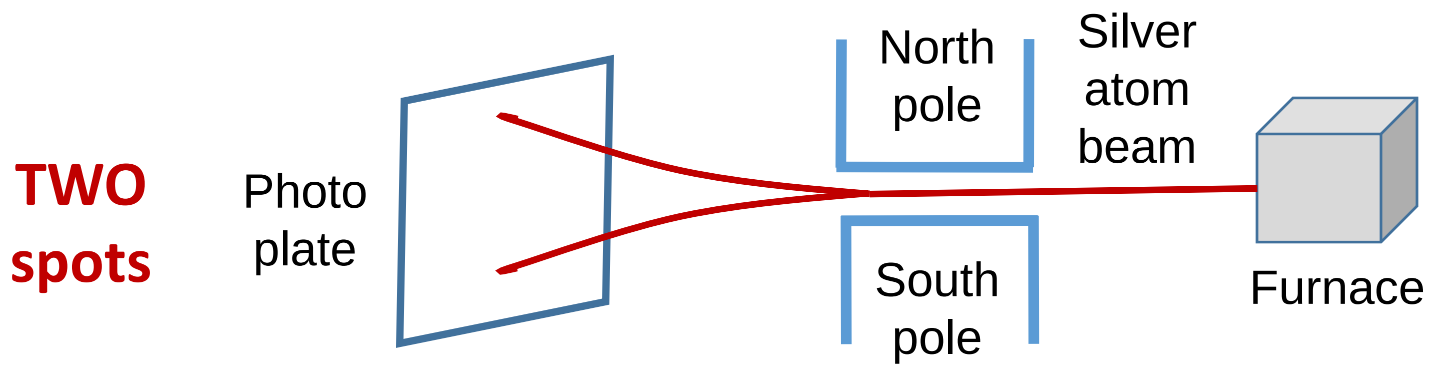


- **No charge movement, rotation of spin**
  - No Ohmic I^2R dissipation, but dissipation due to **damping**

Key Issue **There is dissipation due to applying charge voltage/current**

Spin: Experimental discovery (1922)

- In 1920s, multiplicity of spectra cannot be explained with space quantization rules
- Anomalous Zeeman effect
- In **1922, Stern-Gerlach experiment**



- Hydrogen, Sodium, Silver atoms
  - ✓ orbital angular momentum is zero
- Kronig, Uhlenbeck, Goudsmit (**1925)**
- Pauli and Dirac

Magnetic flux density associated with orbitals

Prove $\mu_B B_n = \frac{1}{4}\left(\frac{\alpha^4 Z^4}{n^5}\right) m_0 c^2$

Bohr magneton $\mu_B = \frac{e\hbar}{2m_0}$

$\alpha = \frac{1}{137}$ Fine structure constant

$$E = \frac{1}{2} m_0 v^2 - \frac{Ze^2}{4\pi\varepsilon_0 r}$$

Centripetal force = Coulomb force

$$\frac{m_0 v^2}{r} = \frac{Ze^2}{4\pi\varepsilon_0 r^2}$$

$$E_n = -\frac{m_0 e^4 Z^2}{2(4\pi\varepsilon_0 \hbar)^2}\frac{1}{n^2}$$

Ionization energy 13.6 eV for H atom

Bohr's quantization of angular momentum

$$L_n = m_0 v_n r_n = n\hbar$$

$$v_n = \frac{Ze^2}{4\pi\varepsilon_0 \hbar}\frac{1}{n}$$

$$r_n = n^2 a_Z$$

$$a_Z = \frac{4\pi\varepsilon_0 \hbar^2}{m_0 Z e^2}$$

$$\frac{v_n}{c} = \frac{e^2}{4\pi\varepsilon_0 \hbar c}\frac{Z}{n} = \alpha\frac{Z}{n}$$

Magnetic flux density associated with orbitals

Prove $\mu_B B_n = \frac{1}{4}\left(\frac{\alpha^4 Z^4}{n^5}\right) m_0 c^2$

Bohr magneton $\mu_B = \frac{e\hbar}{2m_0}$

$\alpha = \frac{1}{137}$ Fine structure constant

Thomas's correction (due to changing direction)

$$\boldsymbol{B} = \frac{\boldsymbol{E} \times \boldsymbol{v}}{2c^2}$$

$\boldsymbol{E}$ is electric field

$$v_n = \frac{Ze^2}{4\pi\varepsilon_0 \hbar}\frac{1}{n}$$

$$r_n = n^2 a_Z$$

$$E_n = \frac{Ze}{4\pi\varepsilon_0 r_n^2}$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

$$a_Z = \frac{4\pi\varepsilon_0 \hbar^2}{m_0 Z e^2}$$

$$\mu_B B_n = \mu_B \frac{E_n v_n}{2c^2} = \frac{1}{4}\left(\frac{\alpha^4 Z^4}{n^5}\right) m_0 c^2$$

H atom
6.16 Tesla

Spinning electron: Classical calculation

$$\mu_B B_n = \frac{1}{4}\left(\frac{\alpha^4 Z^4}{n^5}\right) m_0 c^2$$

$$v_n = \frac{Ze^2}{4\pi\varepsilon_0 \hbar}\frac{1}{n}$$

$$m_0 v_s r_e = \left(\frac{1}{2}\right)\hbar$$

r_e is the classical electron radius or Lorentz radius

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_0 c^2} = 2.8\ fm$$

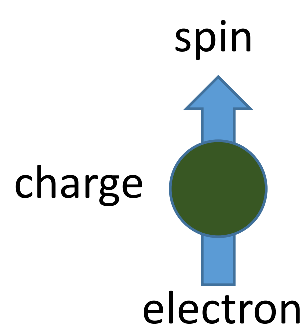
$$m_0 = 9.1 \times 10^{-31} Kg$$
$$\hbar = 1.05 \times 10^{-34} J\text{-}sec$$

$$v_s \cong 67c$$

Incorrect to think in classical terms that the spin of an electron is associated with rotation about its own axis

Electron's Spin: No classical analog

- Apart from having charge, an electron has **spin**
- Spin is a **quantum-mechanical** concept - **no classical analog**

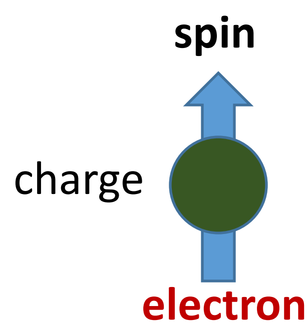


Landau and Lifshitz

"[the spin] property of elementary particles is **peculiar** to quantum theory … [It] has **no classical interpretation** … It would be wholly **meaningless** to imagine the 'intrinsic' angular momentum of an elementary particle as being the result of its **rotation about its own axis**"

Spin: Relativistic quantum mechanics

- Apart from having charge, an electron has **spin**
- Spin is a **quantum-mechanical** concept - **no classical analog**



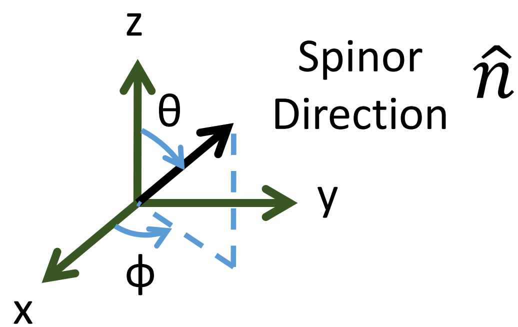
Comes from
relativistic quantum mechanics

Richard Feynman

“It appears to be one of the few places where there is **a rule which can be stated very simply**, but for which **no one has found a simple and easy explanation**. The explanation is down deep in **<u>relativistic quantum mechanics</u>**."

Vectors and spinors: z-direction (B_z)

$$\{\psi\} = \begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$



$$\varepsilon = 0, B_z$$

Spinor's plane: ϕ = ± 90°

$$n_x = sin\theta \cos\phi(t)$$
$$n_y = sin\theta \sin\phi(t)$$
$$n_z = cos\theta$$

$$\frac{dn_x}{dt} = -\omega n_y \qquad \frac{dn_y}{dt} = +\omega n_x$$

$$\psi_{u,d}(t) = \psi_{u,d}(0)e^{\mp i\omega t/2}$$

$$\omega = \frac{2\mu_B B_z}{\hbar}$$

$$\frac{d}{dt}\begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix} = \omega \begin{bmatrix} 0 & -1 & 0 \\ +1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix}$$

$$R_z$$

$$\begin{Bmatrix} \psi_u(t) \\ \psi_d(t) \end{Bmatrix} = \begin{Bmatrix} cos\frac{\theta}{2}e^{-i\phi/2}e^{-i\omega t/2} \\ sin\frac{\theta}{2}e^{+i\phi/2}e^{+i\omega t/2} \end{Bmatrix}$$

$$\frac{d}{dt}\begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix} = \frac{\omega}{2i}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$

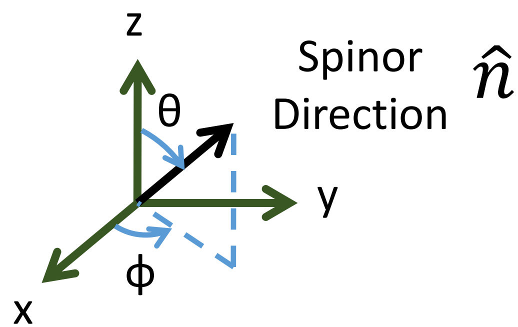
$$\sigma_z$$

$$\phi(t) = \phi(0) + \omega t$$

Vectors and spinors: x-direction (B_x)

$$\{\psi\} = \begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$

$\varepsilon = 0, B_z$



Spinor's plane: ϕ = ± 90°

$$\psi_{u,d}(t) = \psi_{u,d}(0)e^{\mp i\omega t/2}$$

$$\omega = \frac{2\mu_B B_z}{\hbar}$$

$$\begin{Bmatrix} \psi_u(t) \\ \psi_d(t) \end{Bmatrix} = \begin{Bmatrix} \color{red}{cos\frac{\theta}{2}e^{-i\phi/2}}e^{-i\omega t/2} \\ \color{red}{sin\frac{\theta}{2}e^{+i\phi/2}}e^{+i\omega t/2} \end{Bmatrix}$$

$$\phi(t) = \phi(0) + \omega t$$

$$n_x = sin\theta \cos\phi(t)$$
$$n_y = sin\theta \sin\phi(t)$$
$$n_z = cos\theta$$

$x \rightarrow y$
$y \rightarrow z$
$z \rightarrow x$

$$\frac{dn_x}{dt} = -\omega n_y \qquad \frac{dn_y}{dt} = +\omega n_x$$

$$\frac{d}{dt}\begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix} = \omega \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & +1 & 0 \end{bmatrix} \begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix}$$

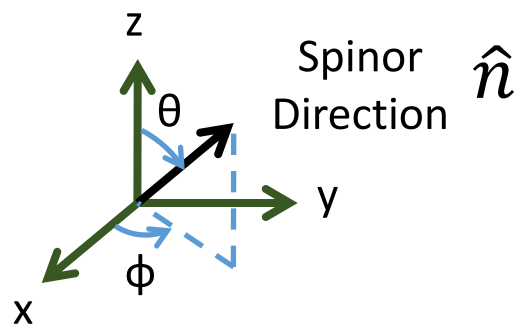
R_x

$$\frac{d}{dt}\begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix} = \frac{\omega}{2i}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$

σ_x

Vectors and spinors: y-direction (B_y)

$$\{\psi\} = \begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$



$$\varepsilon = 0, B_z$$

Spinor's plane: ϕ = ± 90º

$$\psi_{u,d}(t) = \psi_{u,d}(0)e^{\mp i\omega t/2}$$

$$\omega = \frac{2\mu_B B_z}{\hbar}$$

$$\begin{Bmatrix} \psi_u(t) \\ \psi_d(t) \end{Bmatrix} = \begin{Bmatrix} cos\frac{\theta}{2} e^{-i\phi/2} e^{-i\omega t/2} \\ sin\frac{\theta}{2} e^{+i\phi/2} e^{+i\omega t/2} \end{Bmatrix}$$

$$\phi(t) = \phi(0) + \omega t$$

$$n_x = sin\theta \cos\phi(t)$$
$$n_y = sin\theta \sin\phi(t)$$
$$n_z = cos\theta$$

$$x \rightarrow z$$
$$y \rightarrow z$$
$$z \rightarrow y$$

$$\frac{dn_x}{dt} = -\omega n_y \qquad \frac{dn_y}{dt} = +\omega n_x$$

$$\frac{d}{dt}\begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix} = \omega \begin{bmatrix} 0 & 0 & +1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \begin{Bmatrix} n_x \\ n_y \\ n_z \end{Bmatrix}$$

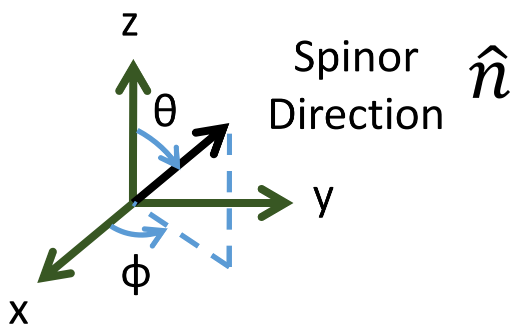
$$R_y$$

$$\frac{d}{dt}\begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix} = \frac{\omega}{2i}\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}\begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$

$$\sigma_y$$

Vectors and spinors: Commutation relations

$$\{\psi\} = \begin{Bmatrix} \psi_u \\ \psi_d \end{Bmatrix}$$



$$n_x = \sin\theta \cos\phi(t)$$
$$n_y = \sin\theta \sin\phi(t)$$
$$n_z = \cos\theta$$

$\varepsilon = 0, B_z$

Spinor's plane: ϕ = ± 90º

$$\frac{dn_x}{dt} = -\omega n_y \qquad \frac{dn_y}{dt} = +\omega n_x$$

$$\psi_{u,d}(t) = \psi_{u,d}(0)e^{\mp i\omega t/2}$$

$$\frac{d\boldsymbol{n}}{dt} = \frac{2\mu_B}{\hbar}(\boldsymbol{B} \times \boldsymbol{n})$$

$$\omega = \frac{2\mu_B B_z}{\hbar}$$

DERIVE

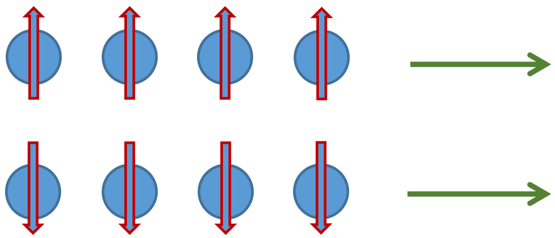
$$R_x R_y - R_y R_x = R_z$$
$$R_y R_z - R_z R_y = R_x$$
$$R_z R_x - R_x R_z = R_y$$

$$\begin{Bmatrix} \psi_u(t) \\ \psi_d(t) \end{Bmatrix} = \begin{Bmatrix} \cos\frac{\theta}{2} e^{-i\phi/2} e^{-i\omega t/2} \\ \sin\frac{\theta}{2} e^{+i\phi/2} e^{+i\omega t/2} \end{Bmatrix}$$

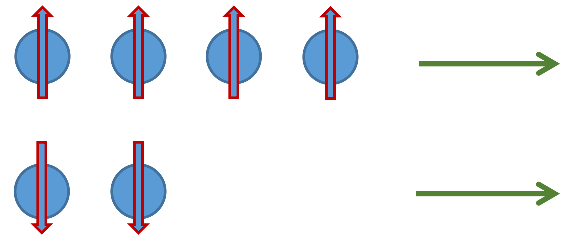
$$\sigma_x \sigma_y - \sigma_y \sigma_x = 2i\sigma_z$$
$$\sigma_y \sigma_z - \sigma_z \sigma_y = 2i\sigma_x$$
$$\sigma_z \sigma_x - \sigma_x \sigma_z = 2i\sigma_y$$

$$\phi(t) = \phi(0) + \omega t$$

Charge current versus Spin current

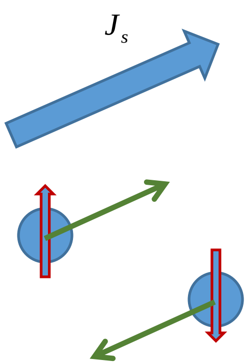


Charge current



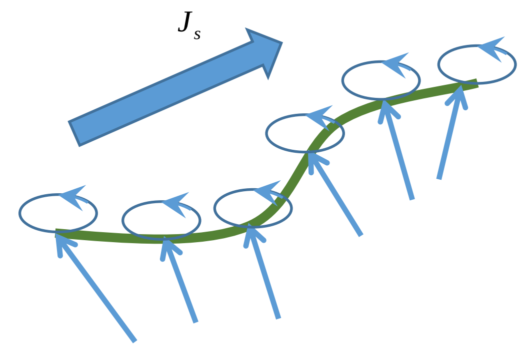
Spin-polarized spin current

Charge → Spin
Spin-orbit coupling
Pt, Ta, W, CuBi



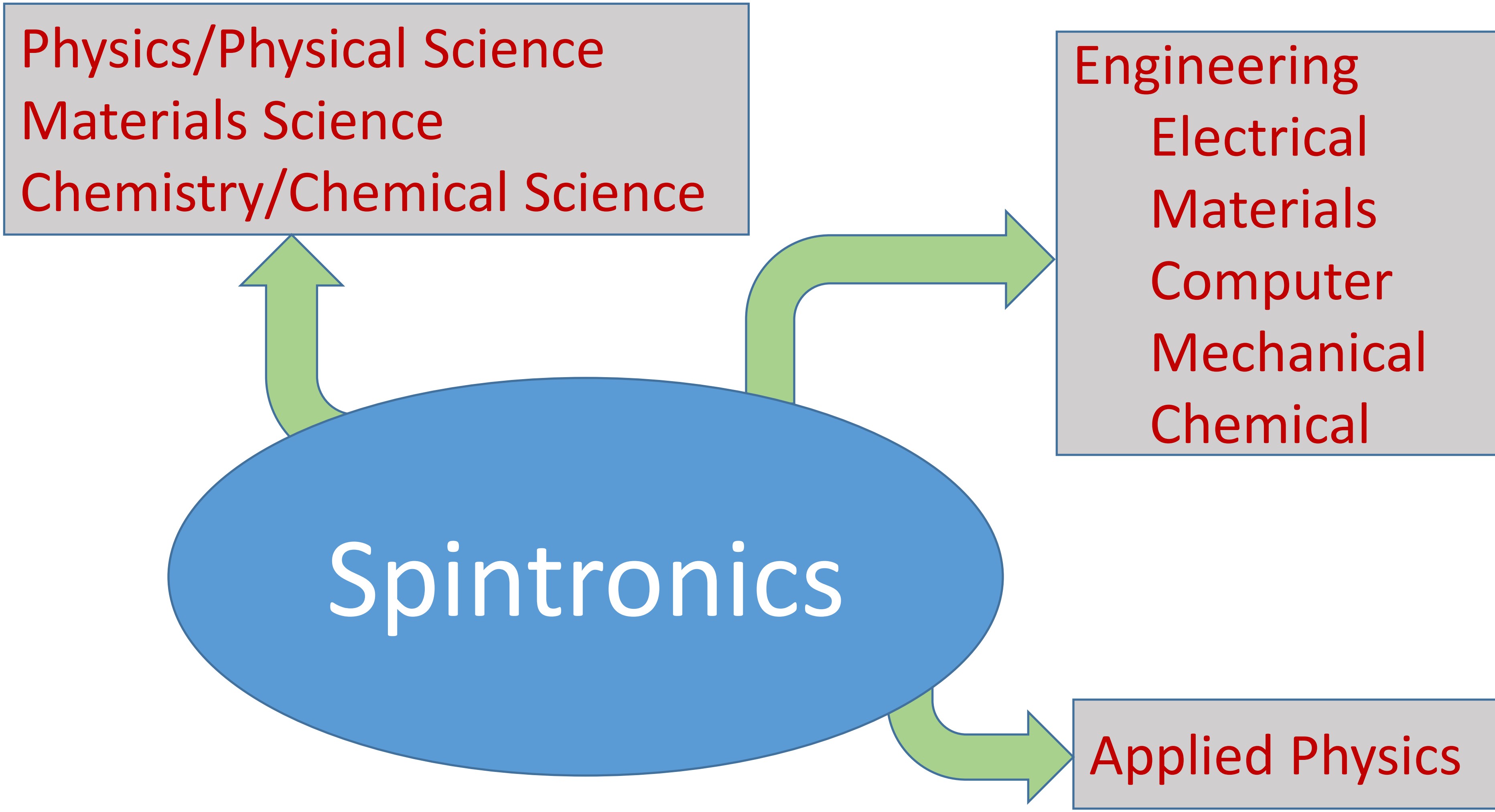
Pure spin current

(Ferri)magnetic insulators
YIG ($Y_3Fe_5O_{12}$)



Spin-wave spin current

Spintronics: Interdisciplinary



Nanoscience and Nanotechnology