FUNDAMENTALS OF NANOELECTRONICS

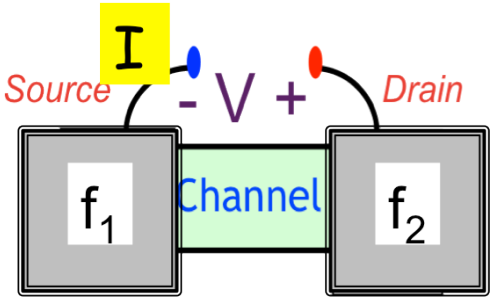
B. Quantum Transport

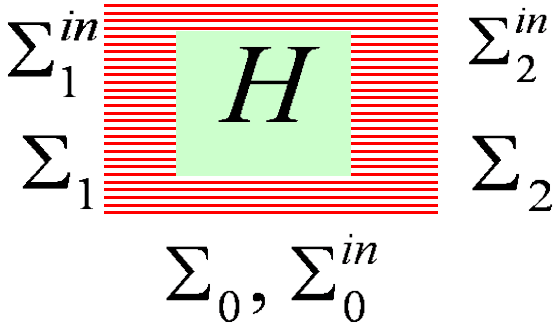
1. Schrodinger Equation
2. Contact-ing Schrodinger
3. More Examples

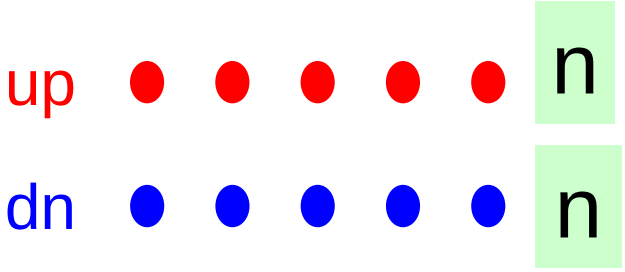
4. Spin Transport →

- 4.1. Introduction
- 4.2. Magnetic contacts
- 4.3. Rotating contacts
- 4.4. Vectors and spinors
- 4.5. Spin-orbit coupling
- 4.6. Spin Hamiltonian
- 4.7. Spin density/current
- 4.8. Spin voltage
- 4.9. Spin circuits
- 4.10. Summing up ..

4.1a Introduction







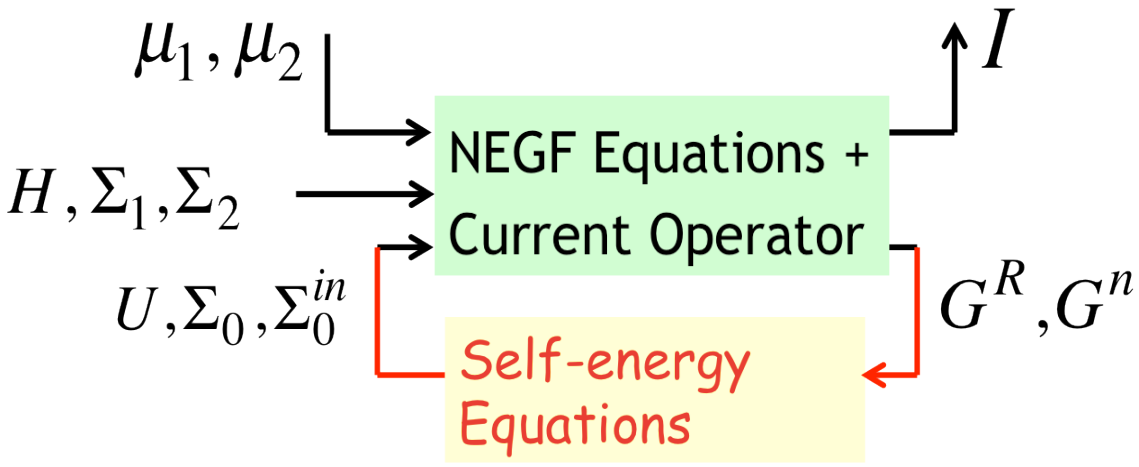
$$G^R = [EI - H - \Sigma]^{-1}$$

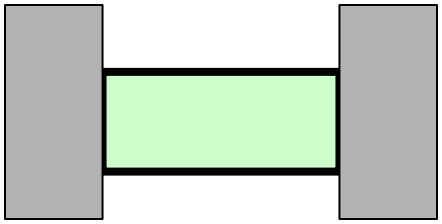
$$G^n = G^R \Sigma^{in} G^A$$

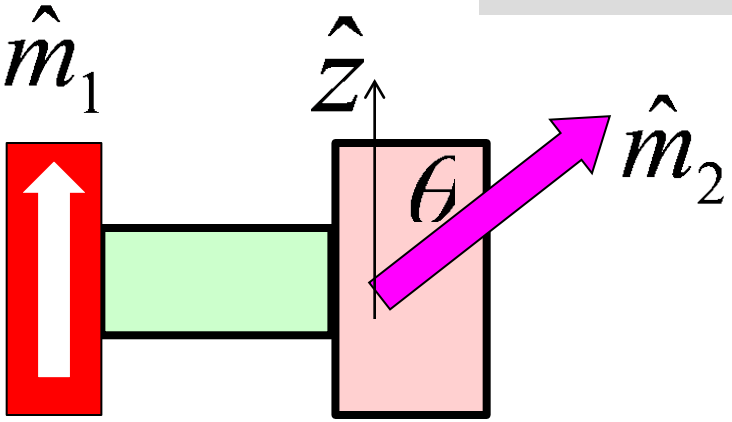
NEGF Equations

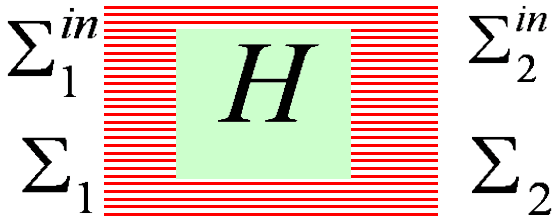
$$I^{op} = \frac{\Sigma G^n - G^n \Sigma^+}{i\hbar} + \frac{\Sigma^{in} G^A - G^R \Sigma^{in}}{i\hbar}$$

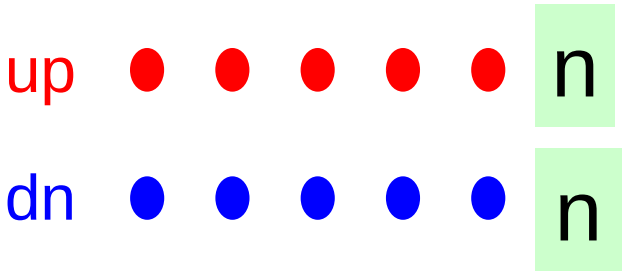
Current Operator

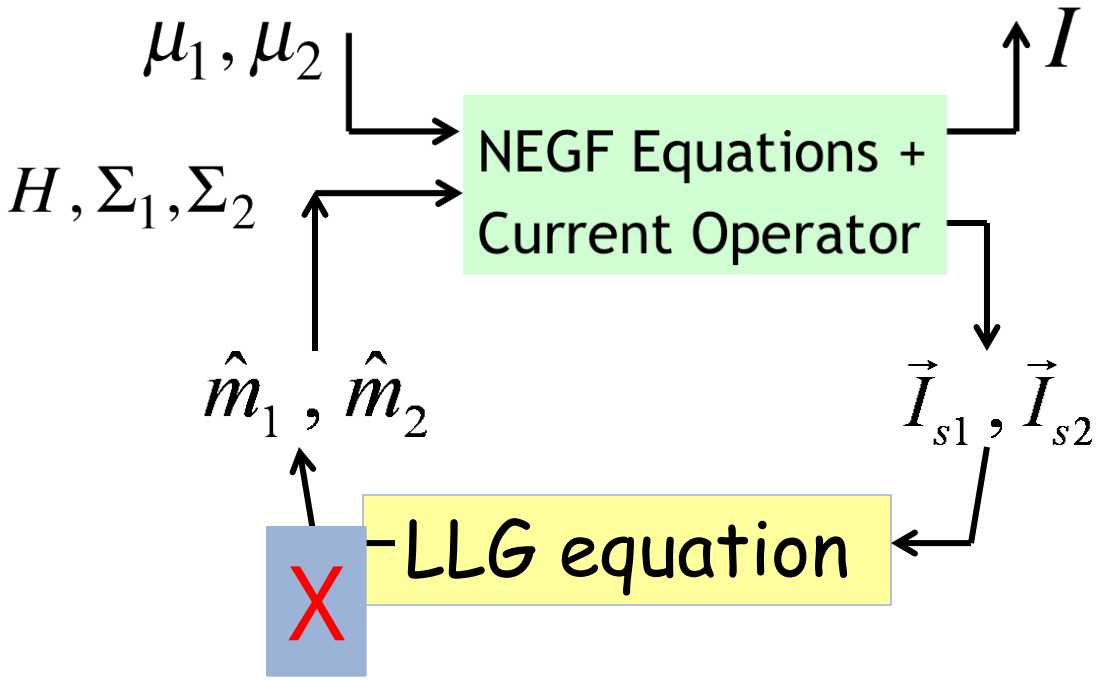





$\hat{m}_1$
$\hat{z}$
θ
$\hat{m}_2$

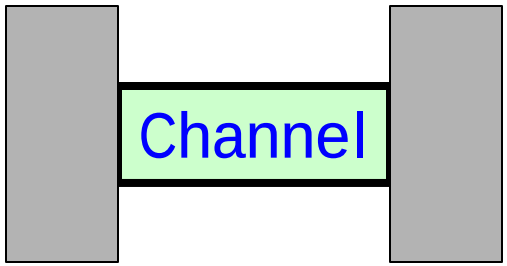

Σ_1^{in}
H
Σ_2^{in}
Σ_1
Σ_2


up
n
dn
n

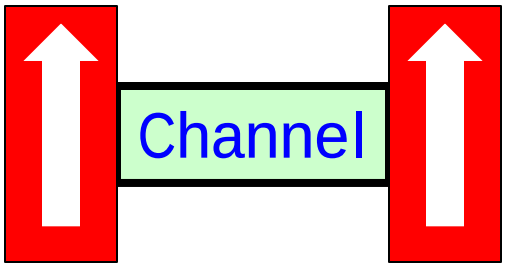

μ_1, μ_2
I
NEGF Equations +
Current Operator
H, Σ_1, Σ_2
$\hat{m}_1, \hat{m}_2$
$\vec{I}_{s1}, \vec{I}_{s2}$
X
LLG equation

4.1c Introduction

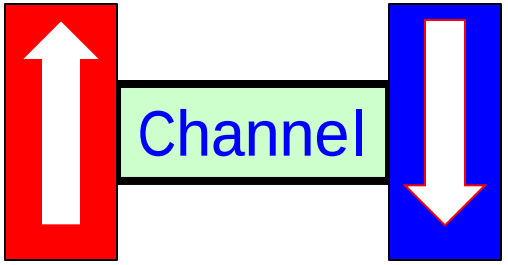
$$R_P \ll R_{AP}$$



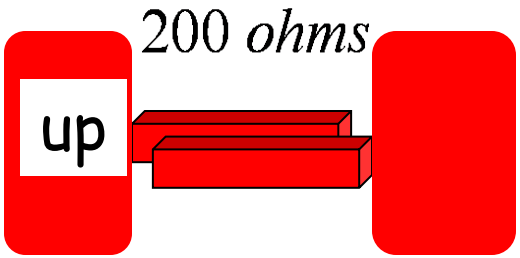
$$\frac{V}{I} = 100\ ohms$$

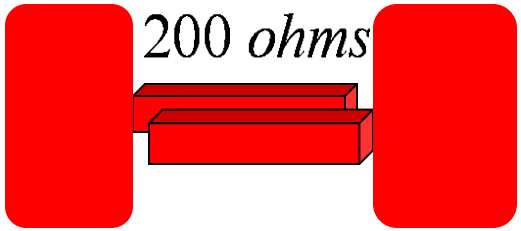


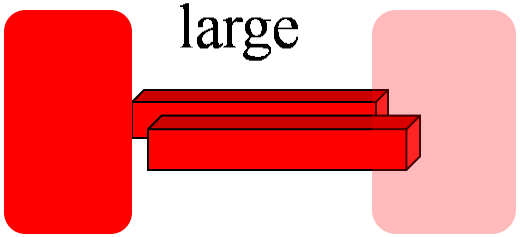
$$\frac{V}{I} \approx 200\ ohms$$

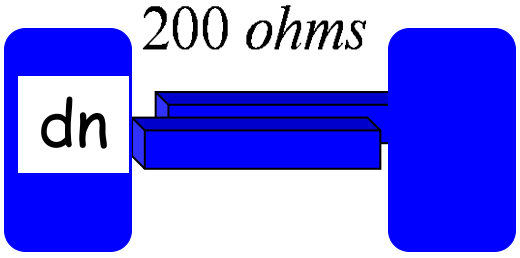


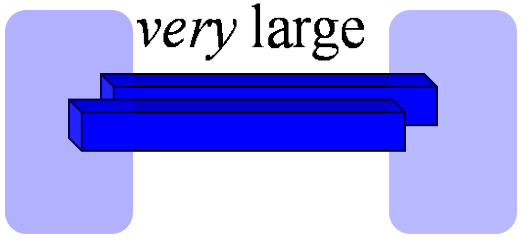
$$\frac{V}{I} >> 200\ ohms$$

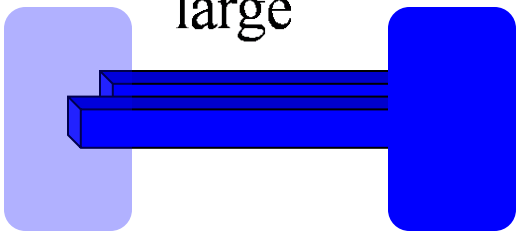






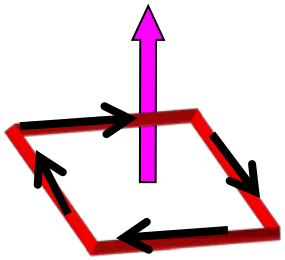






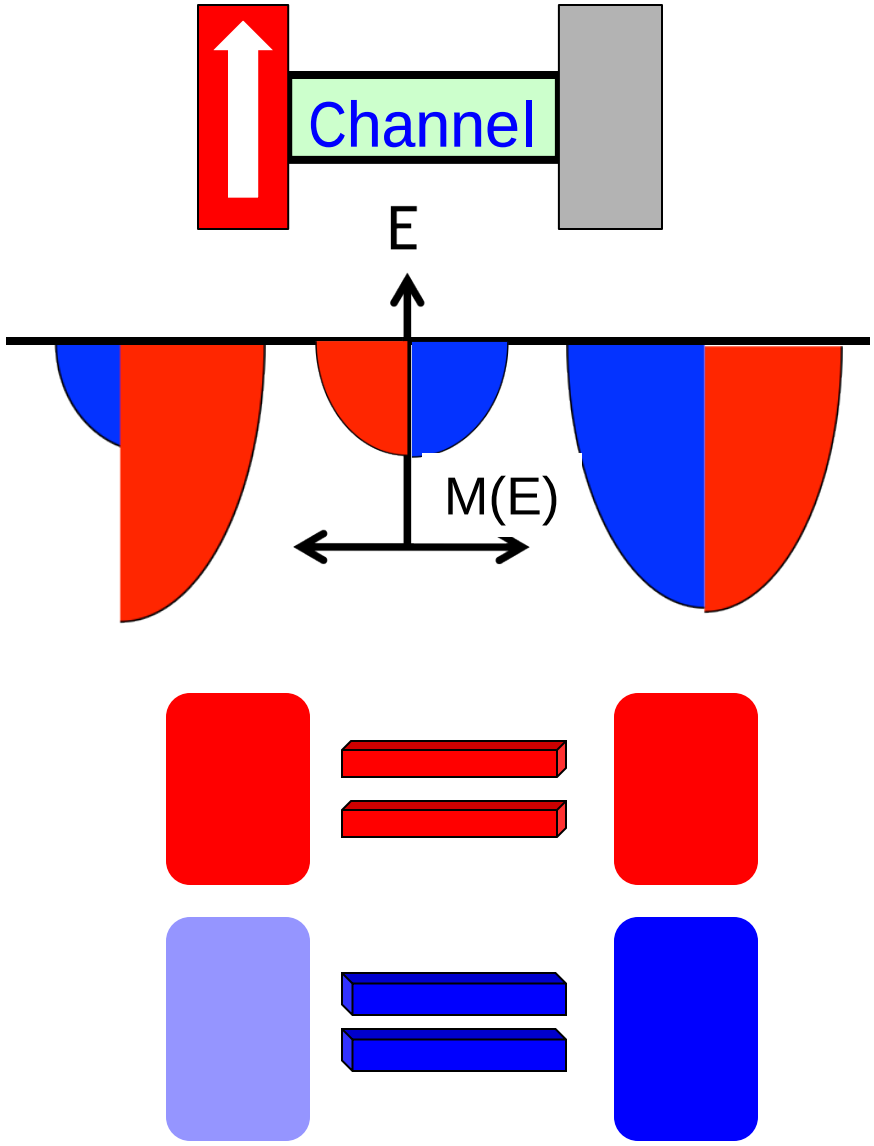
4.1d Introduction

Every electron is like a little "magnet"

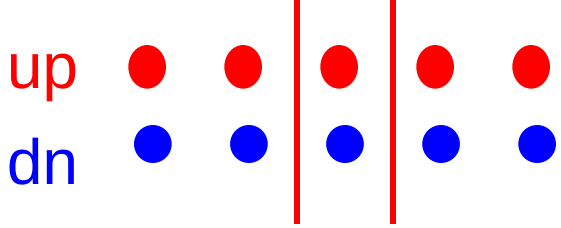


$$\mu_B = \frac{q\hbar}{2m} \sim 10^{-23}\ A - m^2$$

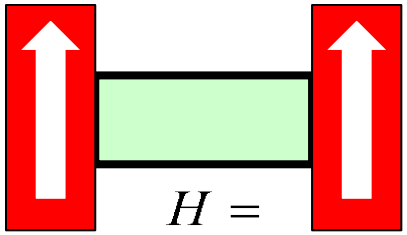
$$= \quad 1\ mA - 1\ Ang^2$$



4.1e Introduction



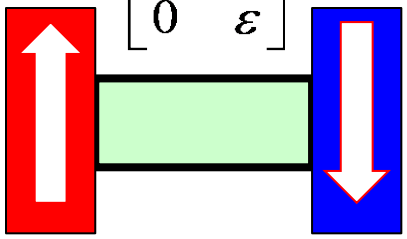
$$\Gamma_1 = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix}$$



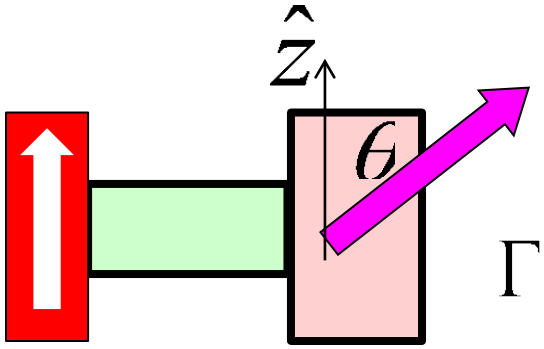
$$\Gamma_2 = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix}$$

$$\Gamma_1 = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix}$$

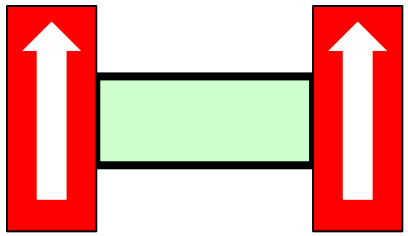
$$\begin{bmatrix} \varepsilon & 0 \\ 0 & \varepsilon \end{bmatrix}$$

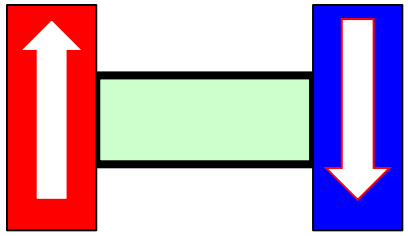


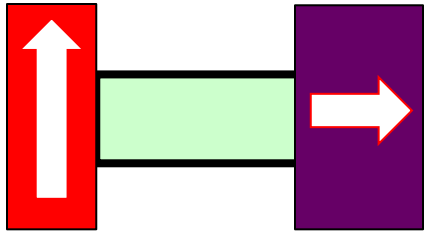
$$\Gamma_2 = \begin{bmatrix} \beta & 0 \\ 0 & \alpha \end{bmatrix}$$



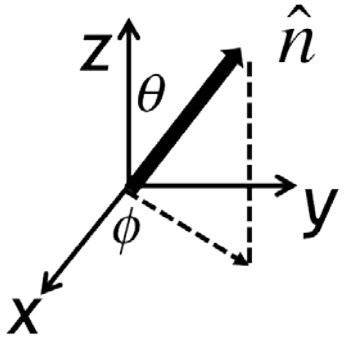
$$\Gamma_2 = ??$$







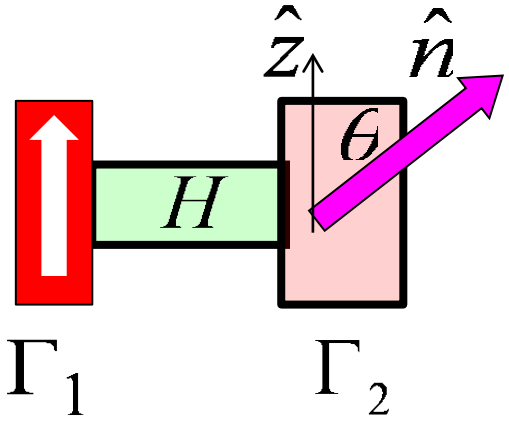
$$\left\{\begin{array}{l} x : \sin\theta\cos\varphi \\ y : \sin\theta\sin\varphi \\ z : \cos\theta \end{array}\right\}$$



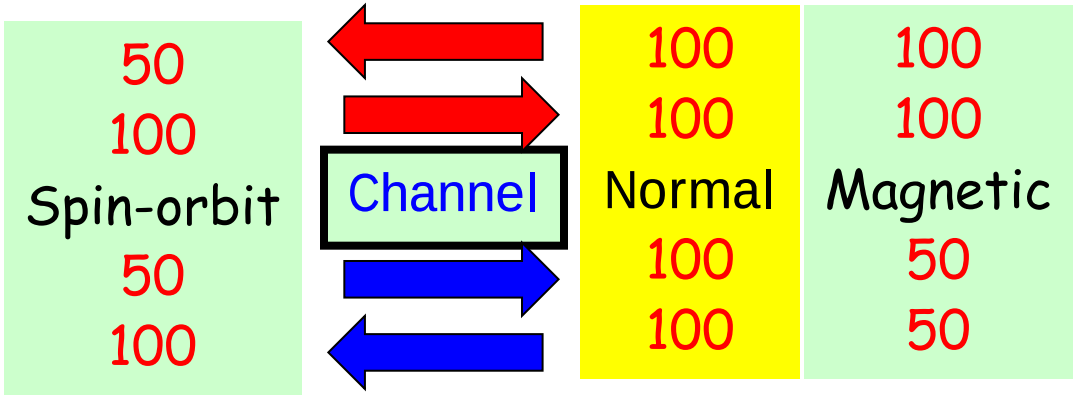
$$c \equiv \cos\theta/2\; e^{-i\varphi/2}$$

$$s \equiv \sin\theta/2\; e^{+i\varphi/2}$$

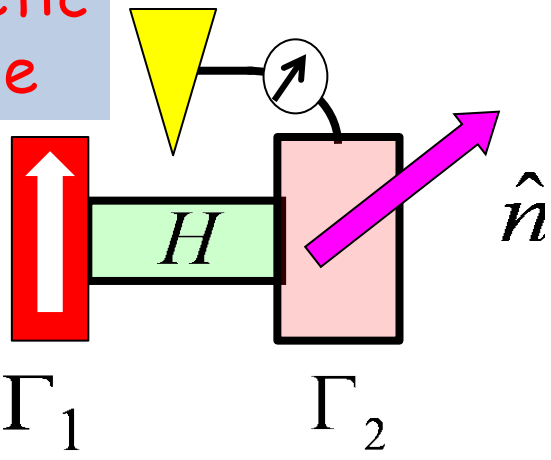
4.1g Introduction



Spin-orbit coupling

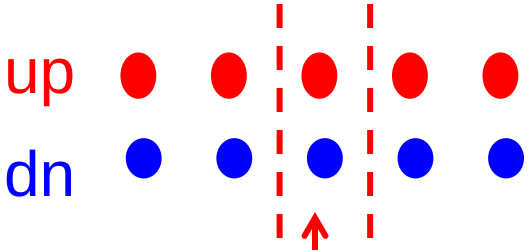


Magnetic Probe



75 up
25 dn

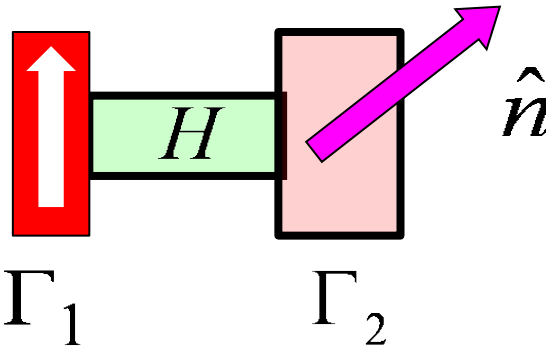
$$N = 100$$
$$S_z = 50$$

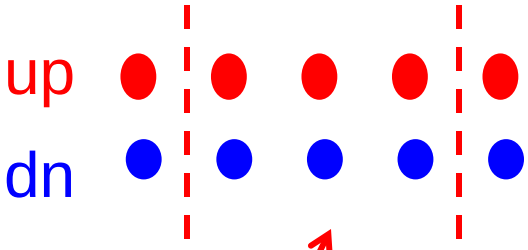


$$\frac{N+S_z}{2} = 75$$
$$\frac{N-S_z}{2} = 25$$

$$\begin{Bmatrix} V \\ \vec{V}_s \end{Bmatrix} \leftarrow [N, \vec{S}]$$

$$G^n = \frac{1}{2}\begin{bmatrix} N+S_z & \\ & N-S_z \end{bmatrix}$$





$$\begin{Bmatrix} V \\ \vec{V}_s \end{Bmatrix} \leftarrow [N, \vec{S}] \rightarrow \begin{Bmatrix} I \\ \vec{I}_s \end{Bmatrix}$$

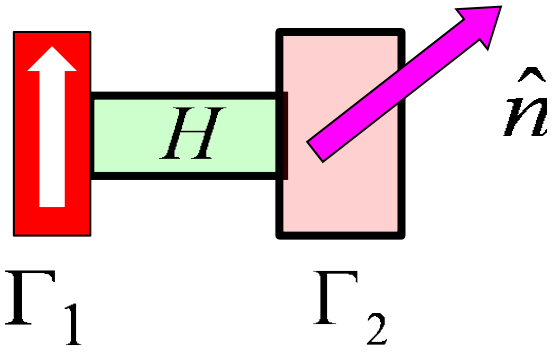
Simpler description

4n components

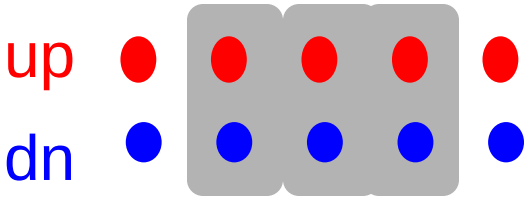
	1up	1dn	2up	2dn	3up	3dn
1up	$[N_1, \vec{S}_1]$					
1dn						
2up			$[N_2, \vec{S}_2]$			
2dn						
3up					$[N_3, \vec{S}_3]$	
3dn						

$4n^2$ components

4.1j Introduction



◆ Could provide a paradigm for defining "larger spins"



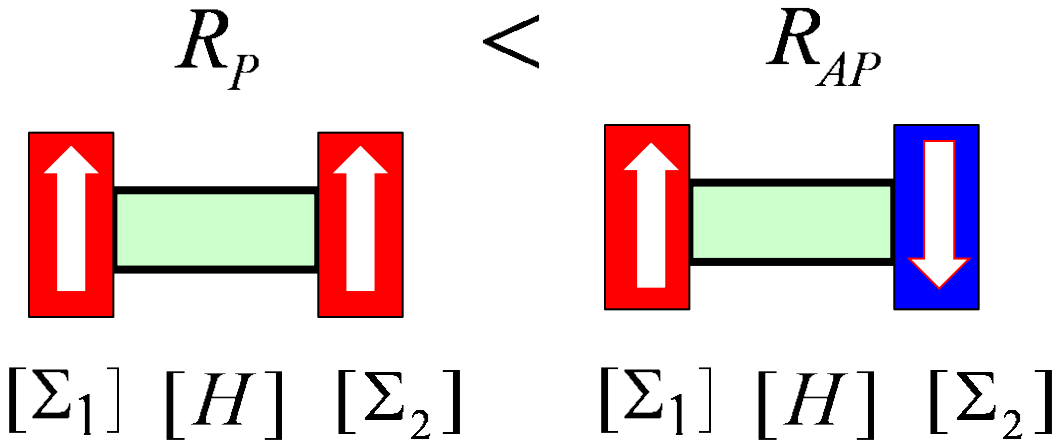
◆ Finding use in spintronics

$$\begin{Bmatrix} V \\ \vec{V}_s \end{Bmatrix} \leftarrow [N, \vec{S}] \rightarrow \begin{Bmatrix} I \\ \vec{I}_s \end{Bmatrix}$$

4n components

Simpler description

Coming up next ..



NEGF Equations

$$\Gamma = i[\Sigma - \Sigma^+]$$

$$G^R = [EI - H - \Sigma_1 - \Sigma_2]^{-1}$$

$$\bar{T}(E) = Trace[\Gamma_1 G^R \Gamma_2 G^A]$$