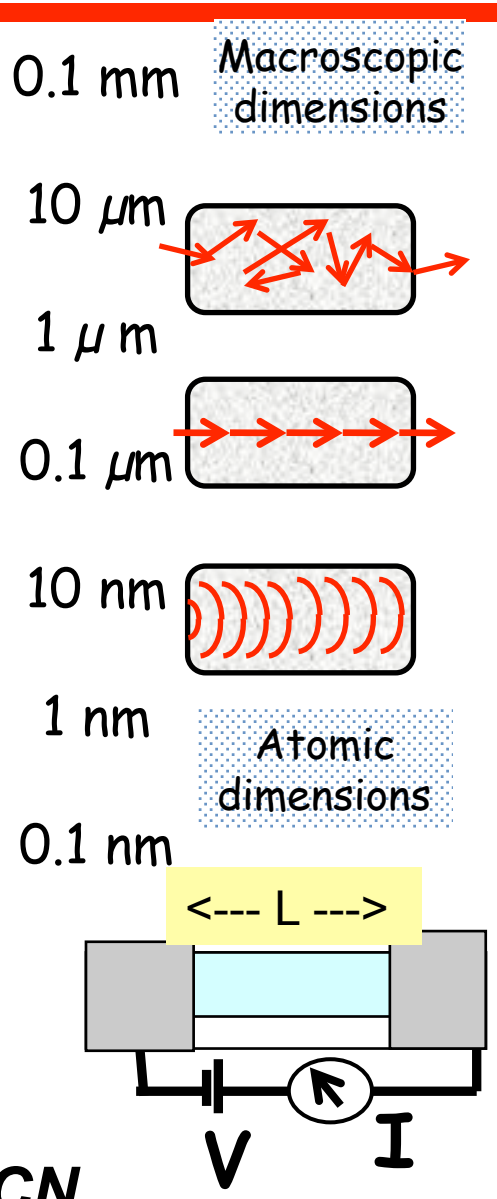
Nanoelectronics



and the

meaning of resistance

1a,b: What and where is the resistance?

2a,b: Quantum transport

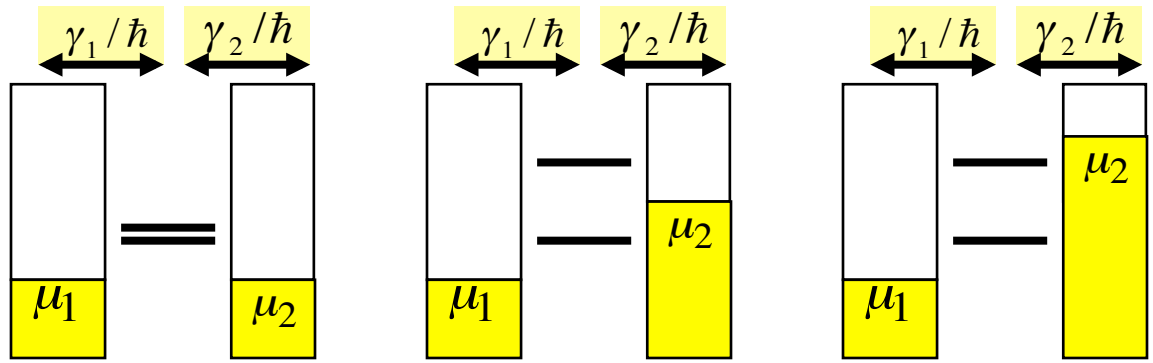
3a,b: Spins and magnets

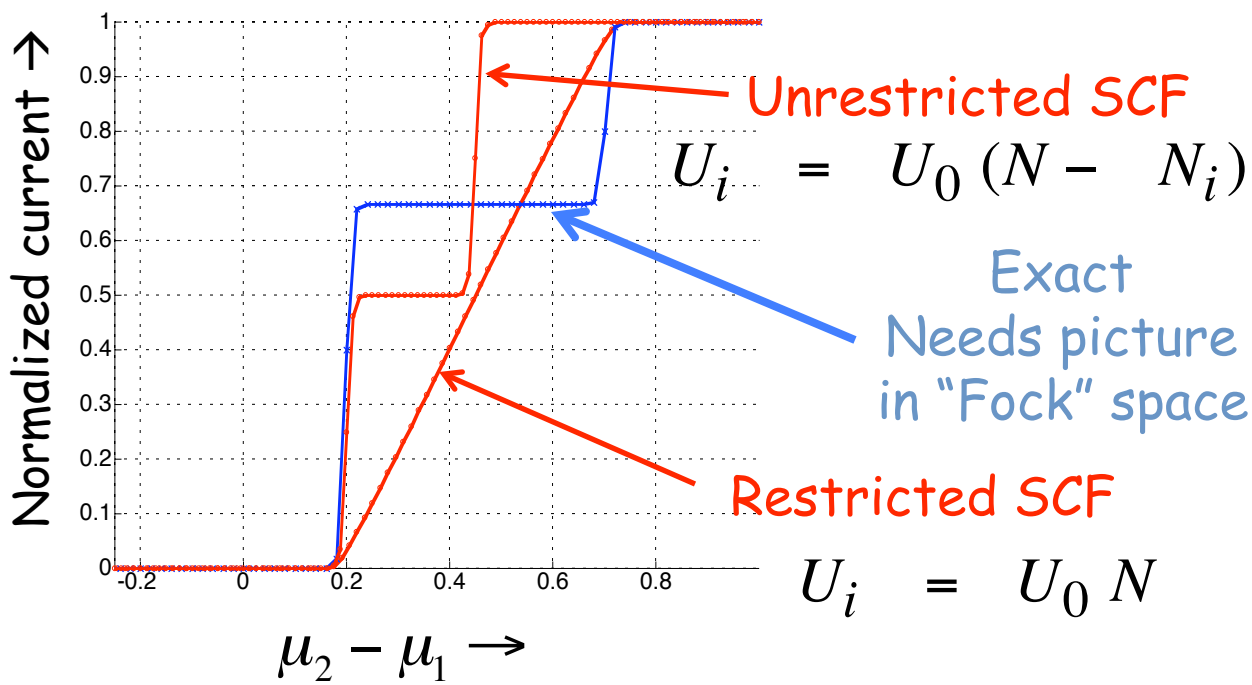
4a,b: Maxwell's demon

5a,b: Correlations and entanglement

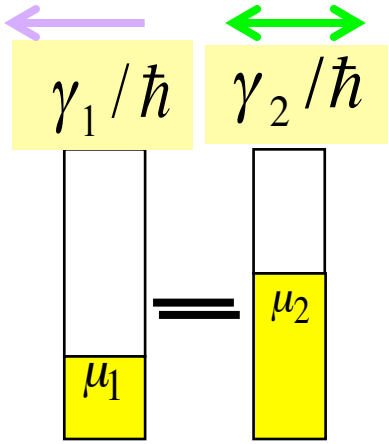
Lecture 5a: Correlation

A simple example to illustrate the meaning of correlation





Coulomb blockade and strong correlation



$f_\uparrow$ and $f_\downarrow$

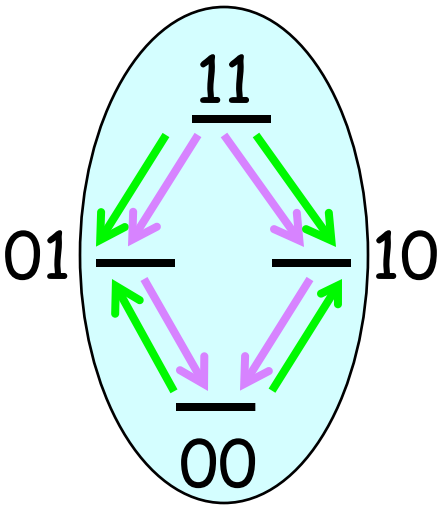
$$P_{00} = (1 - f_\uparrow) * (1 - f_\downarrow)$$

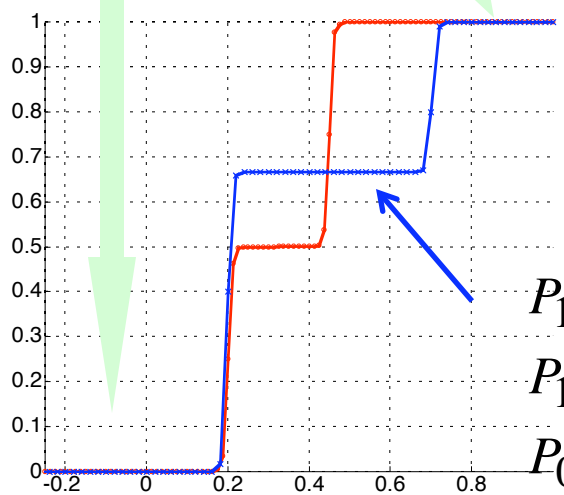
$$P_{10} = f_\uparrow * (1 - f_\downarrow)$$

$$P_{01} = (1 - f_\uparrow) * f_\downarrow$$

$$P_{11} = f_\uparrow * f_\downarrow$$

"UNCORRELATED"





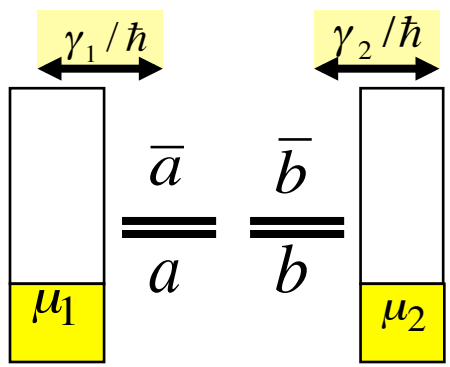
STRONGLY CORRELATED

$$P_{11} = 0$$

$$P_{10} = P_{01} = \gamma_2 / (\gamma_1 + 2\gamma_2)$$

$$P_{00} = \gamma_1 / (\gamma_1 + 2\gamma_2)$$

A simple example to illustrate the meaning of entanglement



	a	b
a	ε	t
b	t	ε

	$\bar{a}$	$\bar{b}$
$\bar{a}$	ε	t
$\bar{b}$	t	ε

Two-electron Hamiltonian

	ab	$\bar{a}\bar{b}$	$a\bar{b}$	$b\bar{a}$	$a\bar{a}$	$b\bar{b}$
ab	2ε	0	0	0	0	0
$\bar{a}\bar{b}$	0	2ε	0	0	0	0
$a\bar{b}$	0	0	2ε	0	t	t
$b\bar{a}$	0	0	0	2ε	t	t
$a\bar{a}$	0	0	t	t	$2\varepsilon + U_0$	0
$b\bar{b}$	0	0	t	t	0	$2\varepsilon + U_0$

Singlets and triplets

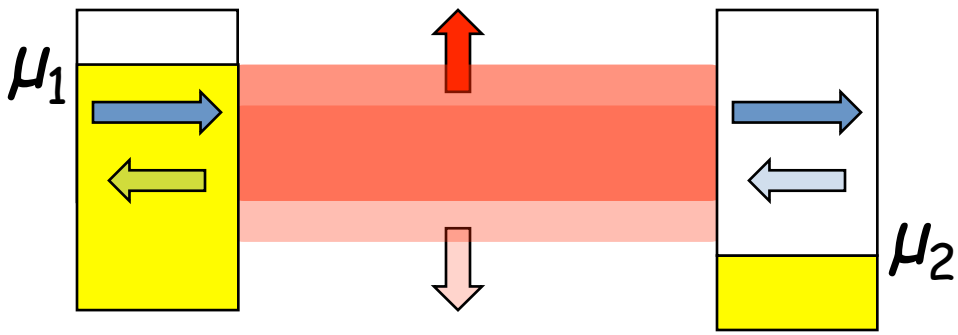
$$2\varepsilon \quad --- \quad ab, \quad \bar{a}\bar{b}, \quad \frac{a\bar{b} - b\bar{a}}{\sqrt{2}} \quad Triplet$$

$$2\varepsilon - \delta \quad - \quad c\frac{a\bar{b} - b\bar{a}}{\sqrt{2}} + \quad s\frac{a\bar{a} - b\bar{b}}{\sqrt{2}} \quad Singlet$$

$$c^2 + \quad s^2 = \quad 1$$

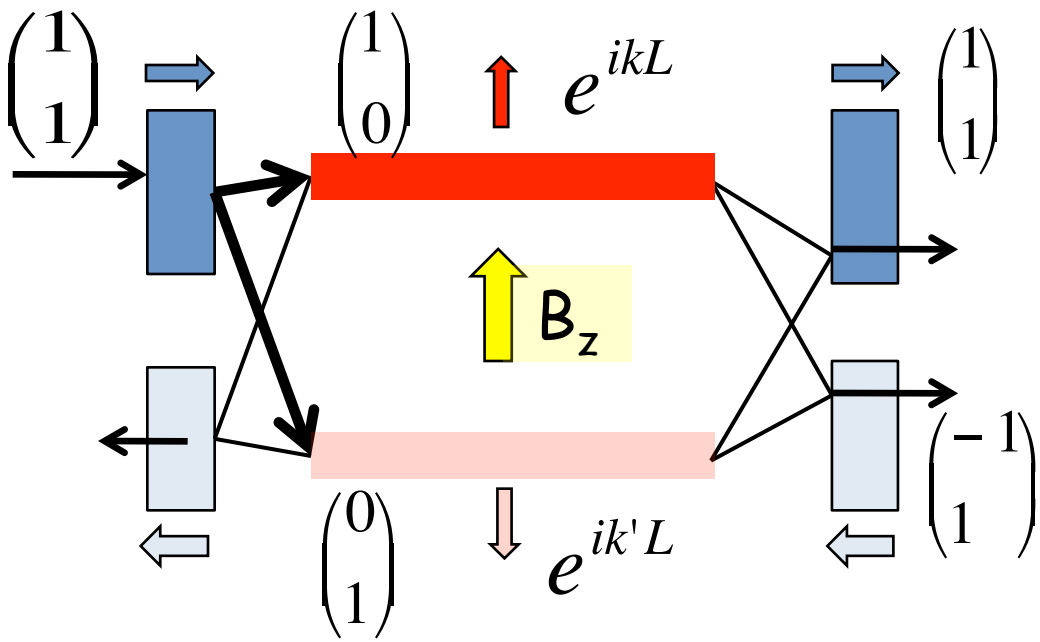
c=s: NOT entangled
c≠s: Entangled

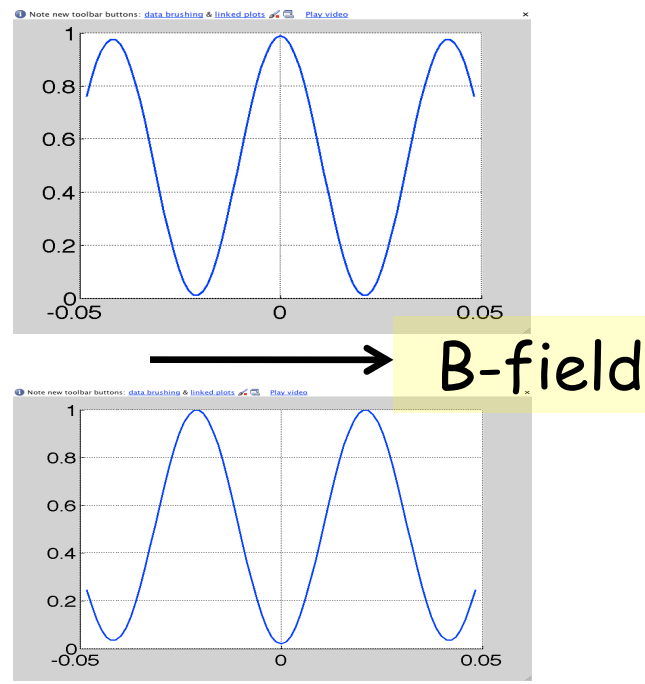
"Two-slit" interference



$$e^{i\delta.L}\begin{pmatrix}1\\0\end{pmatrix} + e^{-i\delta.L}\begin{pmatrix}0\\1\end{pmatrix}$$

$$= \cos\delta.L\begin{pmatrix}1\\1\end{pmatrix} - i\sin\delta.L\begin{pmatrix}-1\\1\end{pmatrix}$$





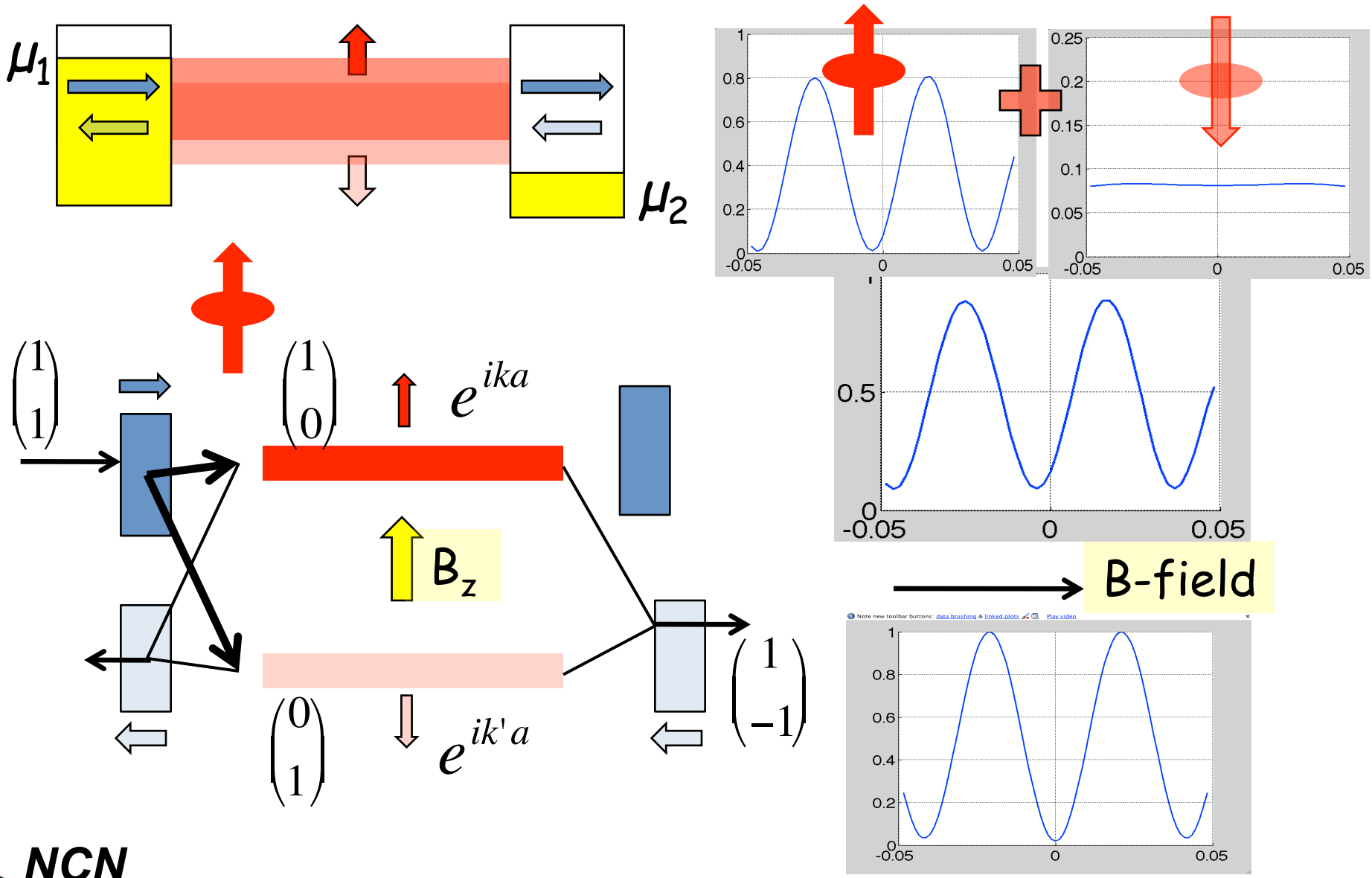
NCN

http://www.nanohub.org/courses/cqt

Supriyo Datta

PURDUE UNIVERSITY

Scattering theory for entangled states



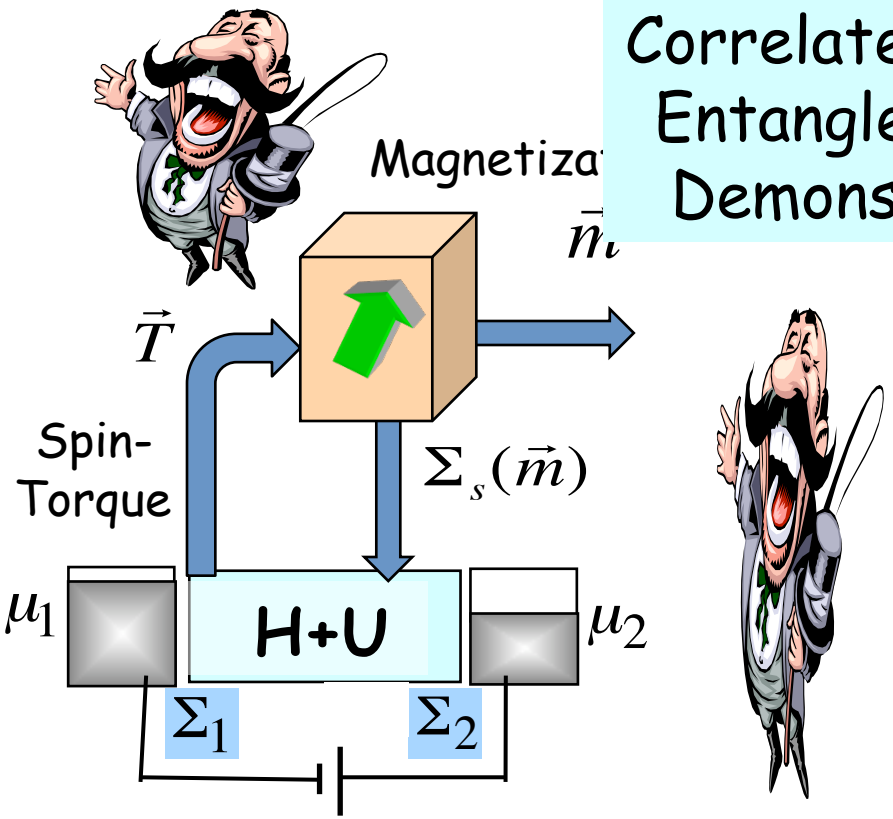
NCN

http://www.nanohub.org/courses/cqt

Supriyo Datta

PURDUE UNIVERSITY

Classifying demons



Correlated/
Entangled
Demons!!

No demon .. just source/drain

Rigid demon .. gates

Elastic demon .. in equilibrium

Inelastic demon .. in equilibrium

Elastic demon .. out-of-equilibrium

Inelastic demon .. out-of-equilibrium

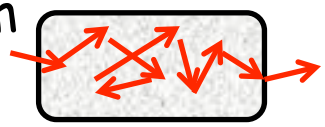
Bistable demon

Nanoelectronics and the meaning of resistance

0.1 mm

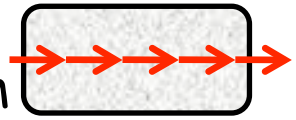
Macroscopic dimensions

10 μm



1 μm

0.1 μm

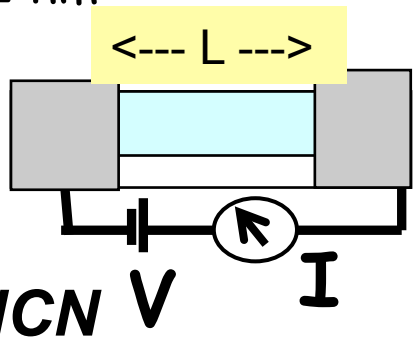


10 nm

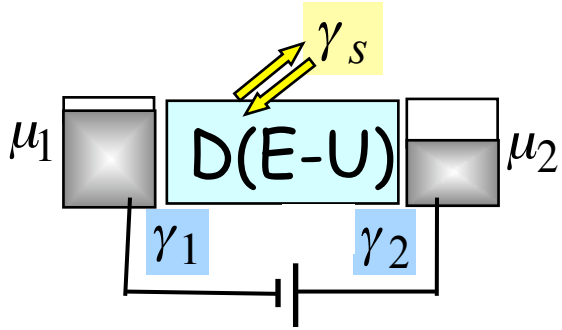
1 nm

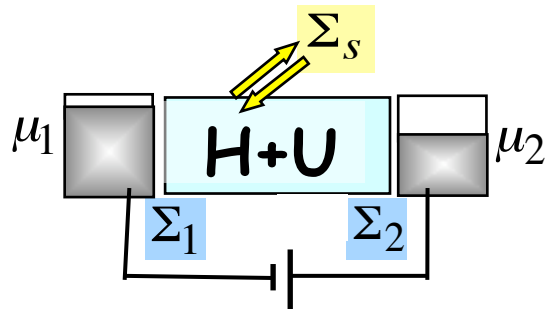
Atomic dimensions

0.1 nm



Lectures 1a,b:
Simple model





Lectures 2a,b:
Microscopic model

Lectures 3a,b:
Add spin

Lectures 4a,b:
Energy exchange
and the second law

Lectures 5a,b:
Correlations &
Entanglement

NCN

http://www.nanohub.org/courses/cqt

Supriyo Datta

PURDUE UNIVERSITY