Section 15
Introduction to Non-Equilibrium

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PURDUE UNIVERSITY

School of Electrical and Computer Engineering

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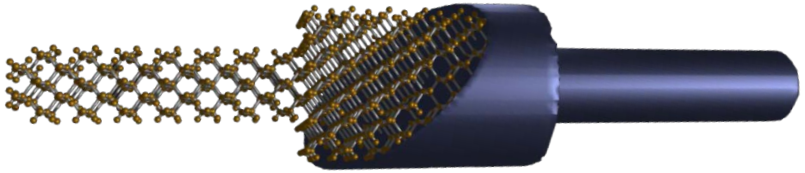

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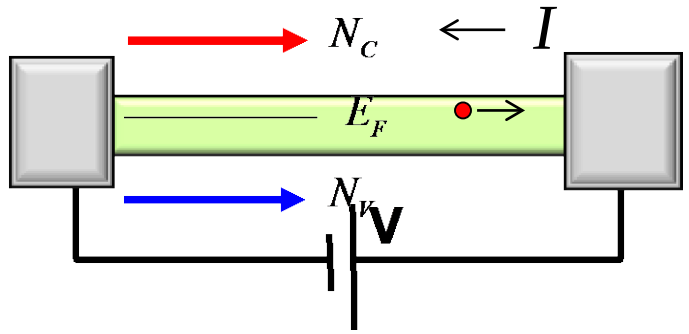
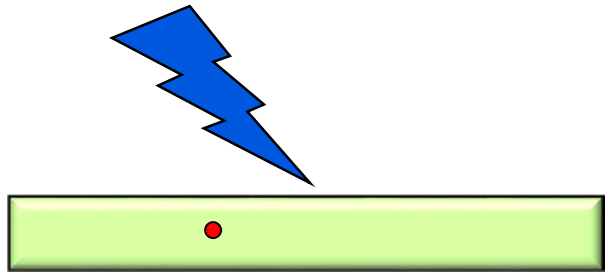
$$= q \times n \times v \times A$$

charge density velocity area





How does the system go BACK to equilibrium?

- **Materials, composition, crystals**
- Tabulated for **"known" bulk materials**

⇒ Quantum Mechanics Mechanics

- Concepts of **density of states and masses**

⇒ Equilibrium Statistical Mechanics

- **Occupation factors**

Transport with scattering, non-equilibrium Stat. Mech.
- Drift-diffusion equation with recombination-generation

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Video

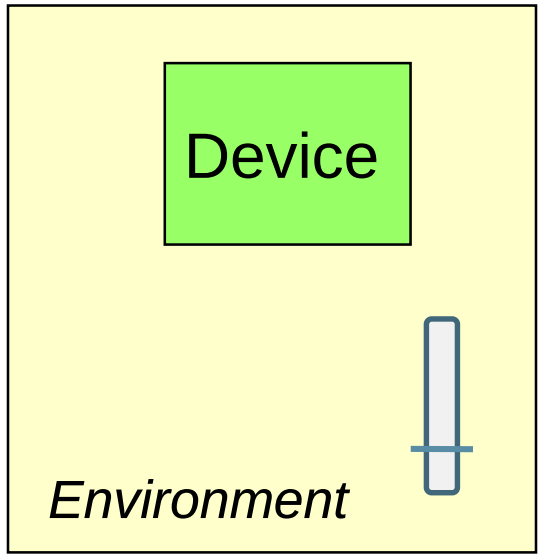
- 15.1 Steady State, Transient, Equilibrium

Video

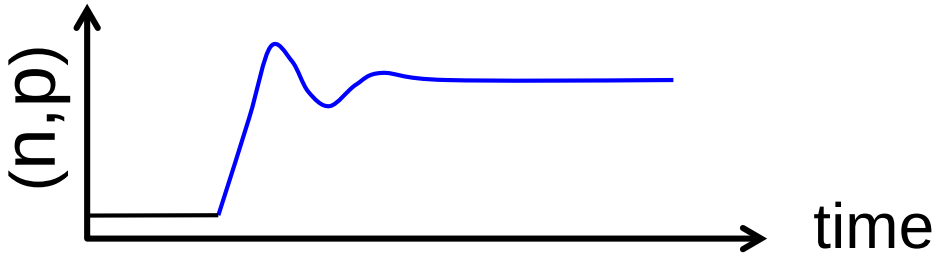
- 15.2 Recombination & Generation Overview

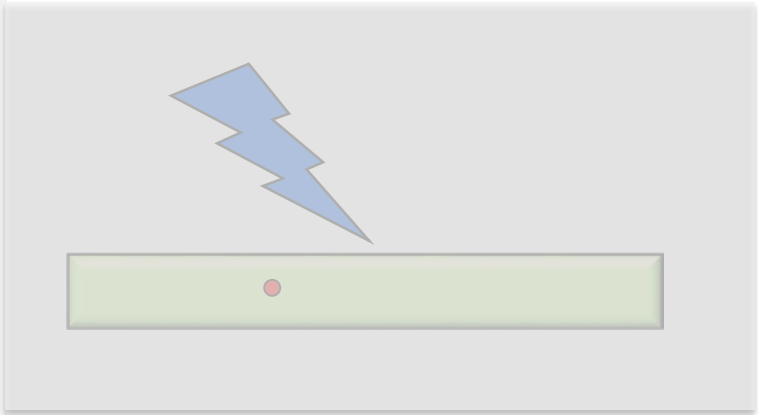
Equilibrium, Steady state, Transient

Equilibrium



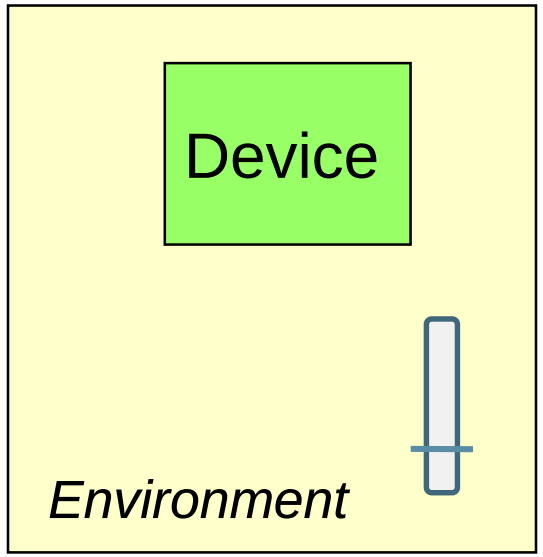
Steady state

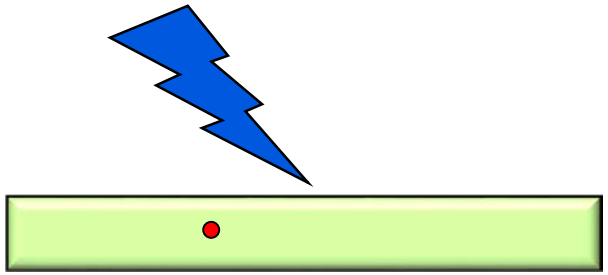




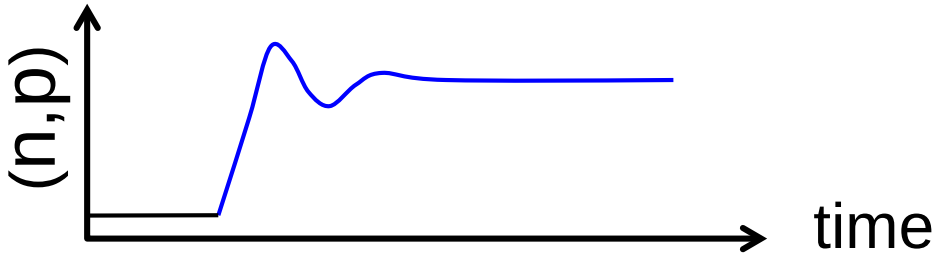
Equilibrium, Steady state, Transient

Equilibrium

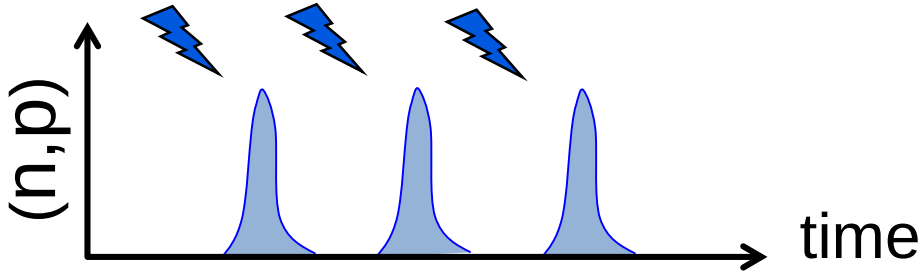




Steady state

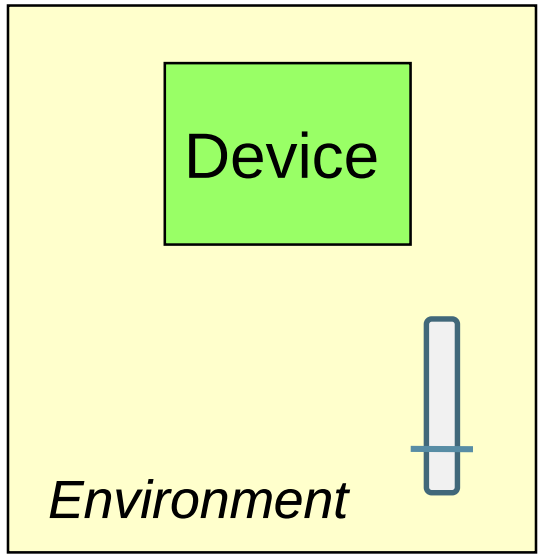


Transient



Detailed Balance: Simple Explanation

Equilibrium



Equilibrium is a very active place

typical semiconductor device there are 1e17 to 1e20 electrons in the conduction band. All electrons carry charge and are occupying their respective DOS.

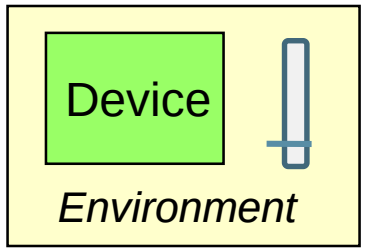
Fermi-Dirac distribution demands exploration of allowed states

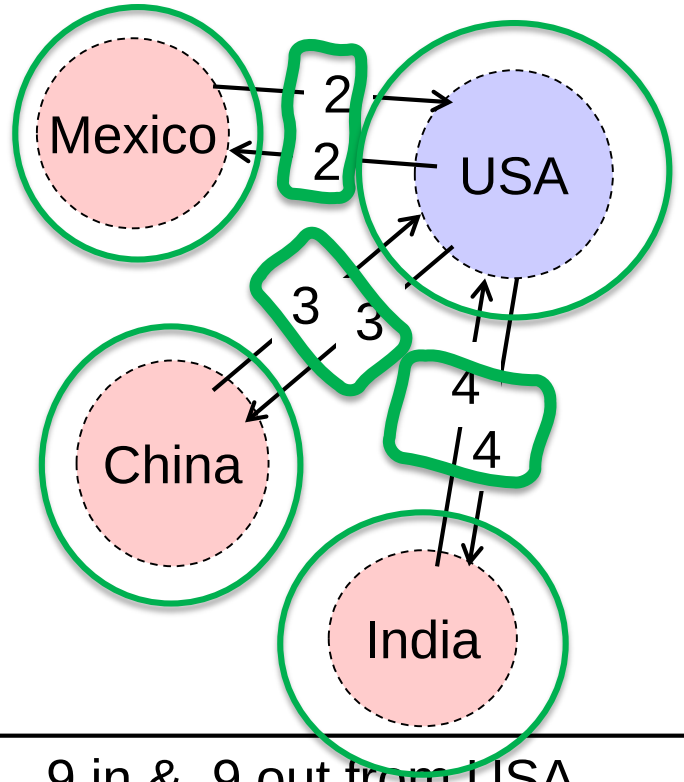
In equilibrium each process is balanced by its counter process => Detailed Balance
=> Externally it looks as if nothing is happening.

This is different from steady state!!!

Detailed Balance: Simple Explanation

Equilibrium





9 in & 9 out from USA
All numbers are people/unit time.

Equilibrium is a very active place

Fermi-Dirac distribution demands exploration of allowed states

In equilibrium each process is balanced by its counter process
=> Detailed Balance

=> Externally it looks as if nothing is happening for each site.

This is different from steady state!!!

The rates of exchange of people (particles) between every pair of countries (energy levels) is balanced. Hence the name “Detailed Balance”.

Detailed balance is the property of equilibrium

The population of each of the countries (energy levels) remains constant under detailed balance.

The concept of detailed balance is powerful, because it can be used for many things

- derive particle distributions Fermi-Dirac, Bose-Einstein
- reduce the number of unknown rate constants by half

Steady State Response

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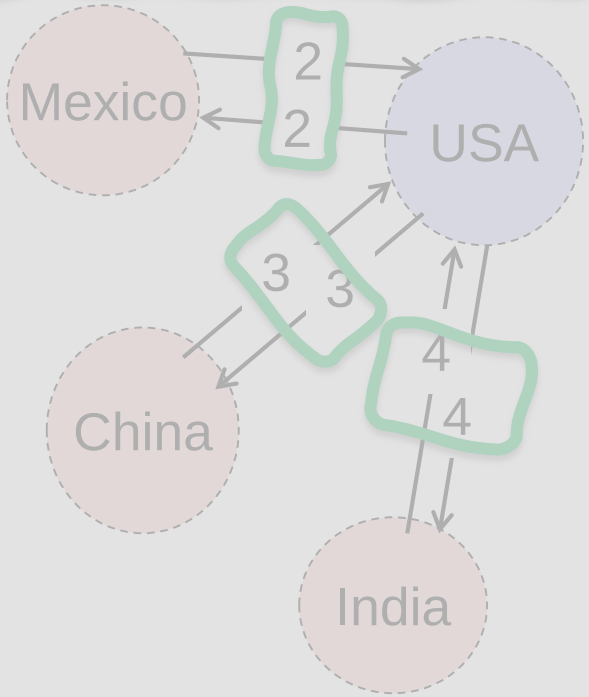

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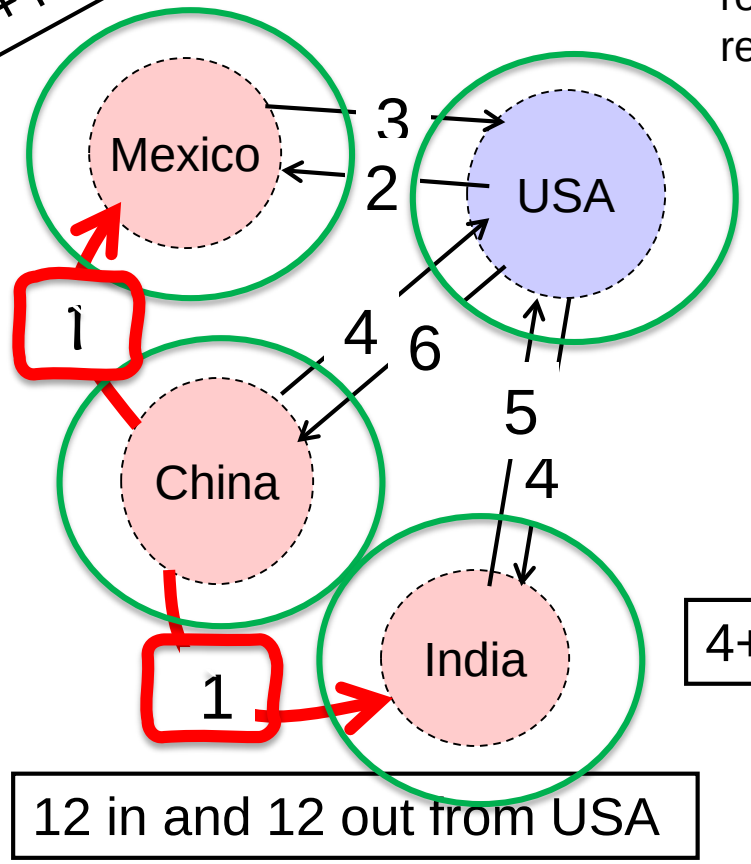
2+1 in and 3 out from Mexico



12 in and 12 out from USA

Disturbing the detailed balance requires non-equilibrium conditions (needs energy). Unidirectional forces (red lines) can create such Non-equilibrium conditions

The population of a country (energy level) remains constant with time after steady state is reached.

4+1 in and 5 out from India

Steady State Response

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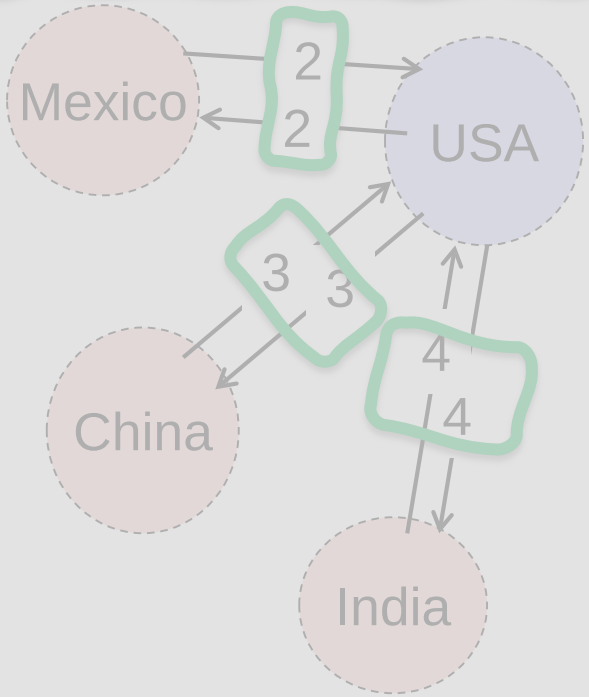

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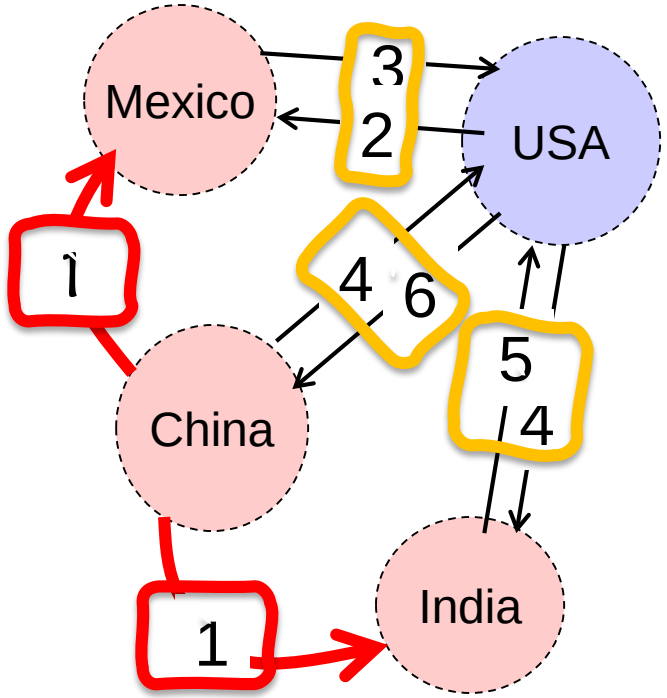

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The population of a country (energy level) remains constant with time after steady state is reached.

The rates of exchange of people (particles) between every pair of countries (energy levels) is NOT balanced.

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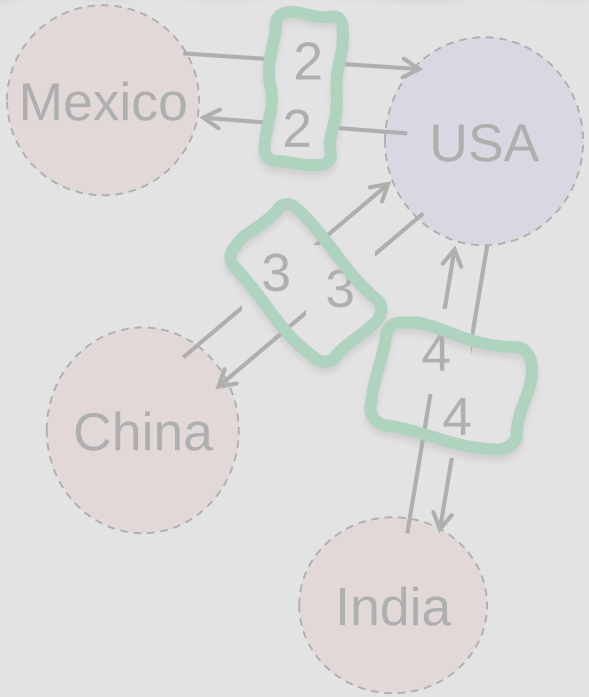

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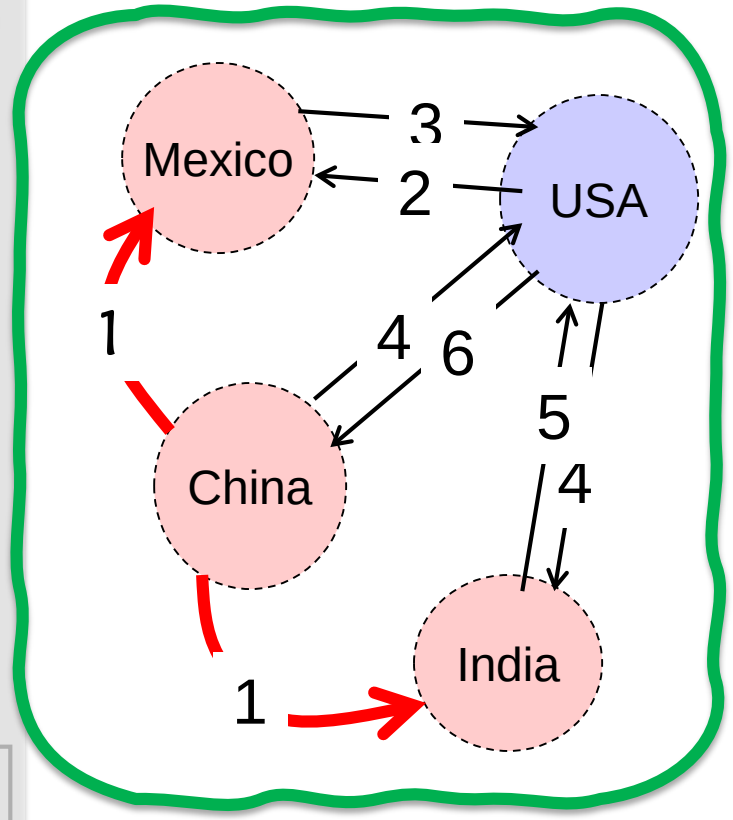

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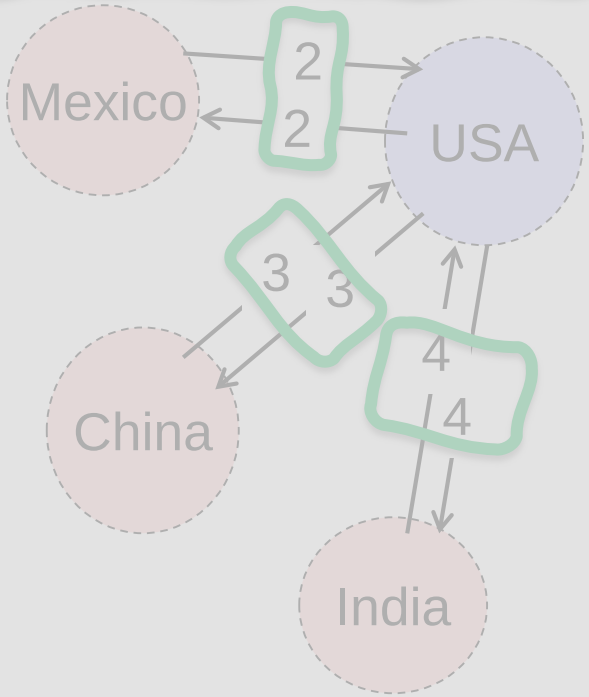

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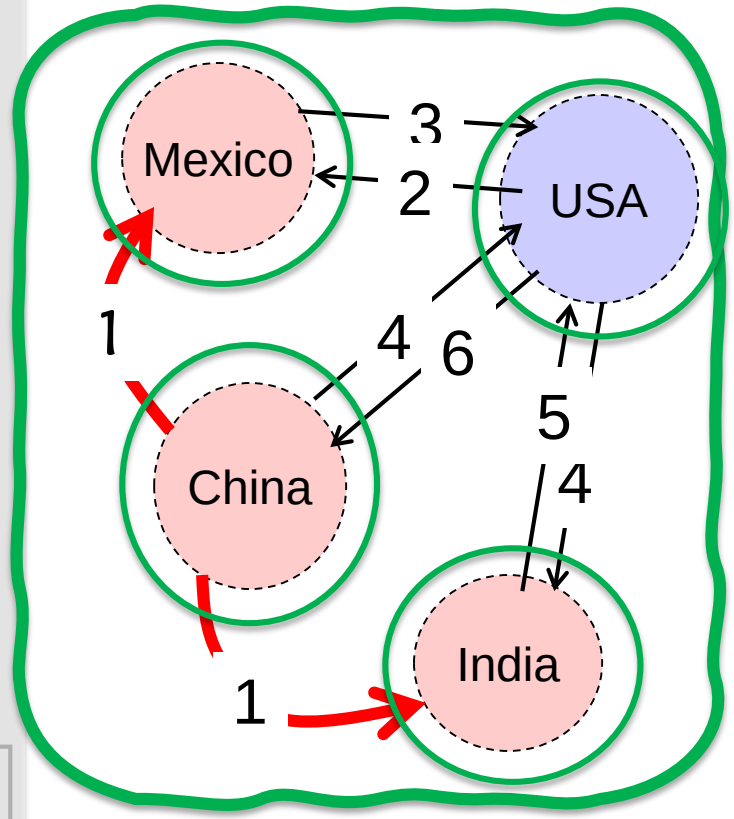

Disturbing the detailed balance requires non-equilibrium conditions (needs energy). Unidirectional forces (red lines) can create such Non-equilibrium conditions

The population of a country (energy level) remains constant with time after steady state is reached.

The rates of exchange of people (particles) between every pair of countries (energy levels) is NOT balanced.

The flux at steady state is balanced overall,

One can use the requirement that net flux at steady state be zero to calculate steady state population of a country

Transient Response

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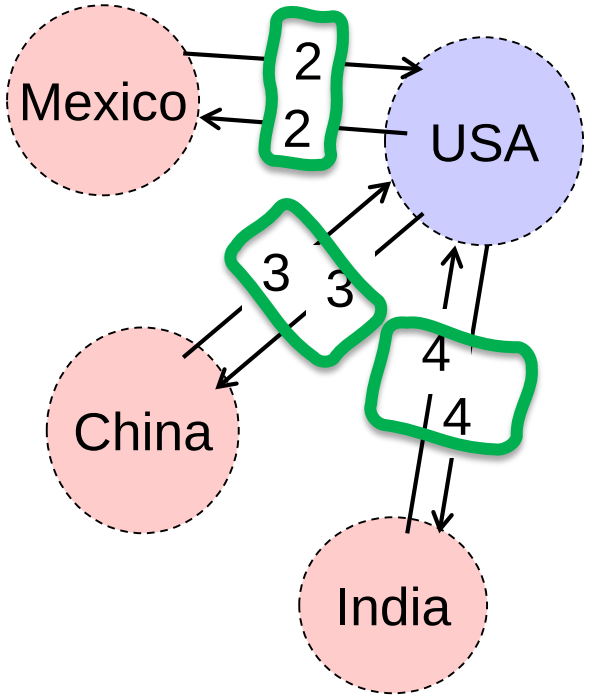

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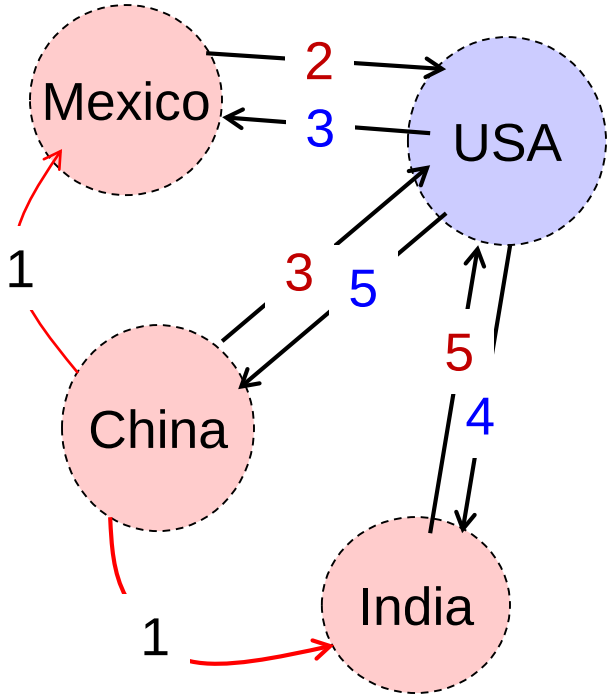
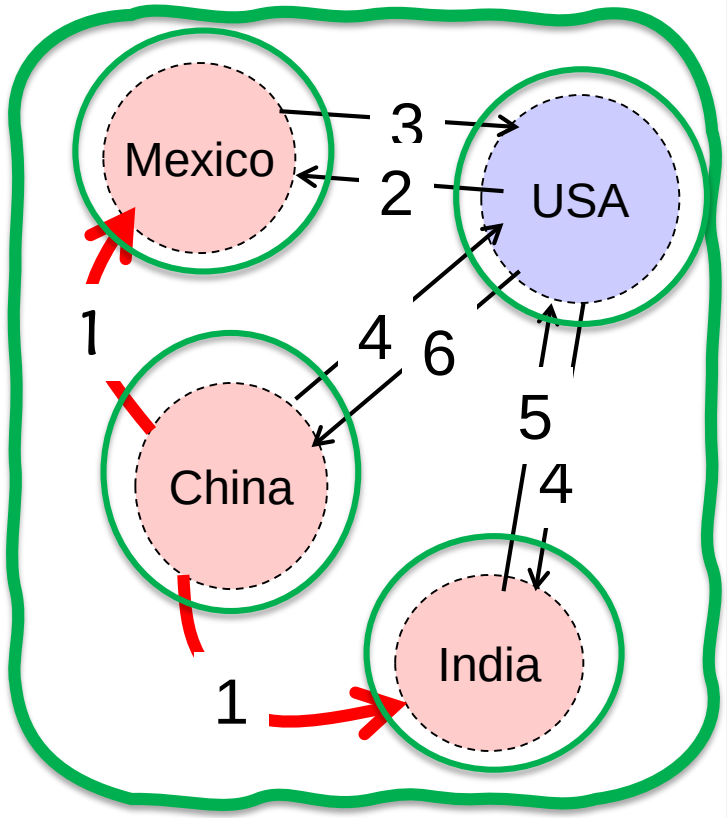
Forced unidirectional connections (red lines) disturbs equilibrium (e.g. 10 in/12 out at time t1 local populations not conserved, but global population is ….
Transient populations



steady state
=> Externally it looks as if nothing is happening for the overall system.



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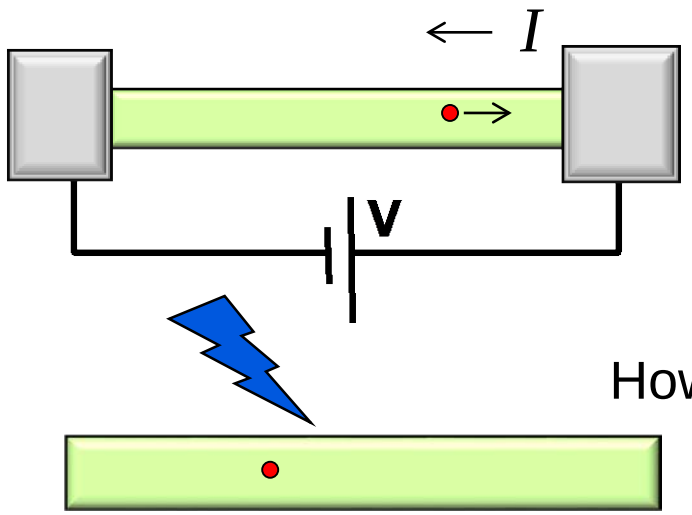

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charge density velocity area

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  - »Critical conceptual differences!
  - »Need to understand these!
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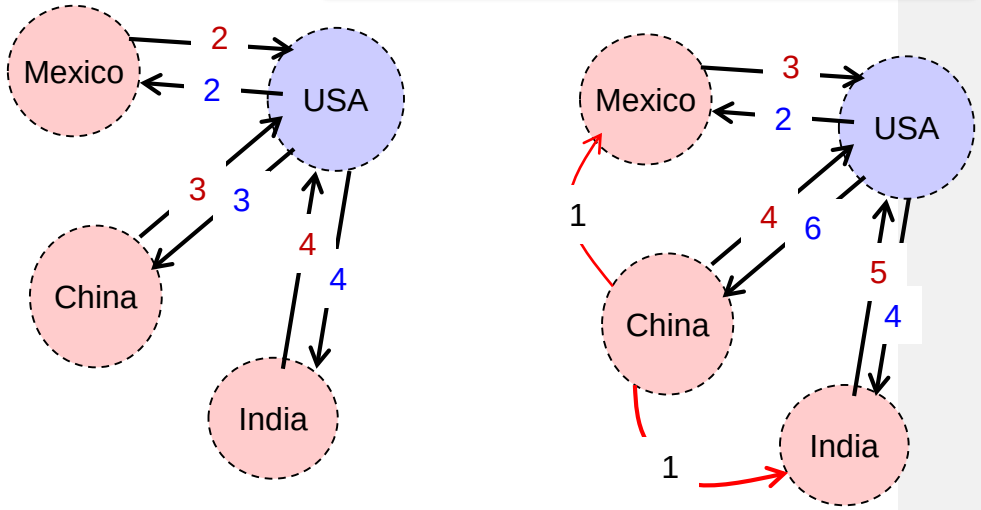
Video1

Video 2



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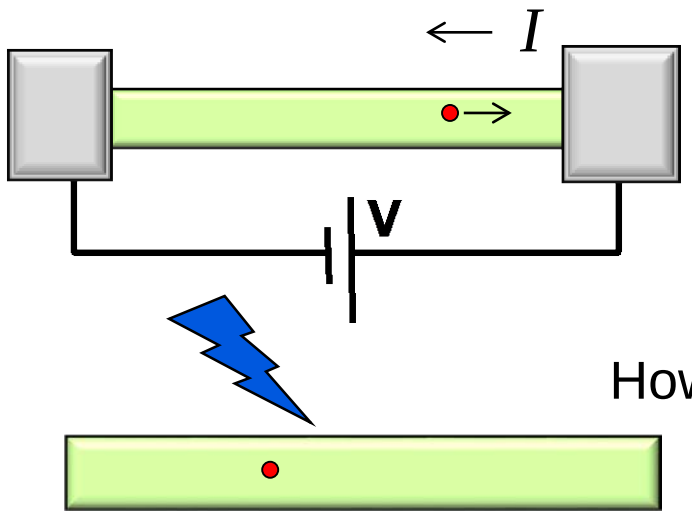

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