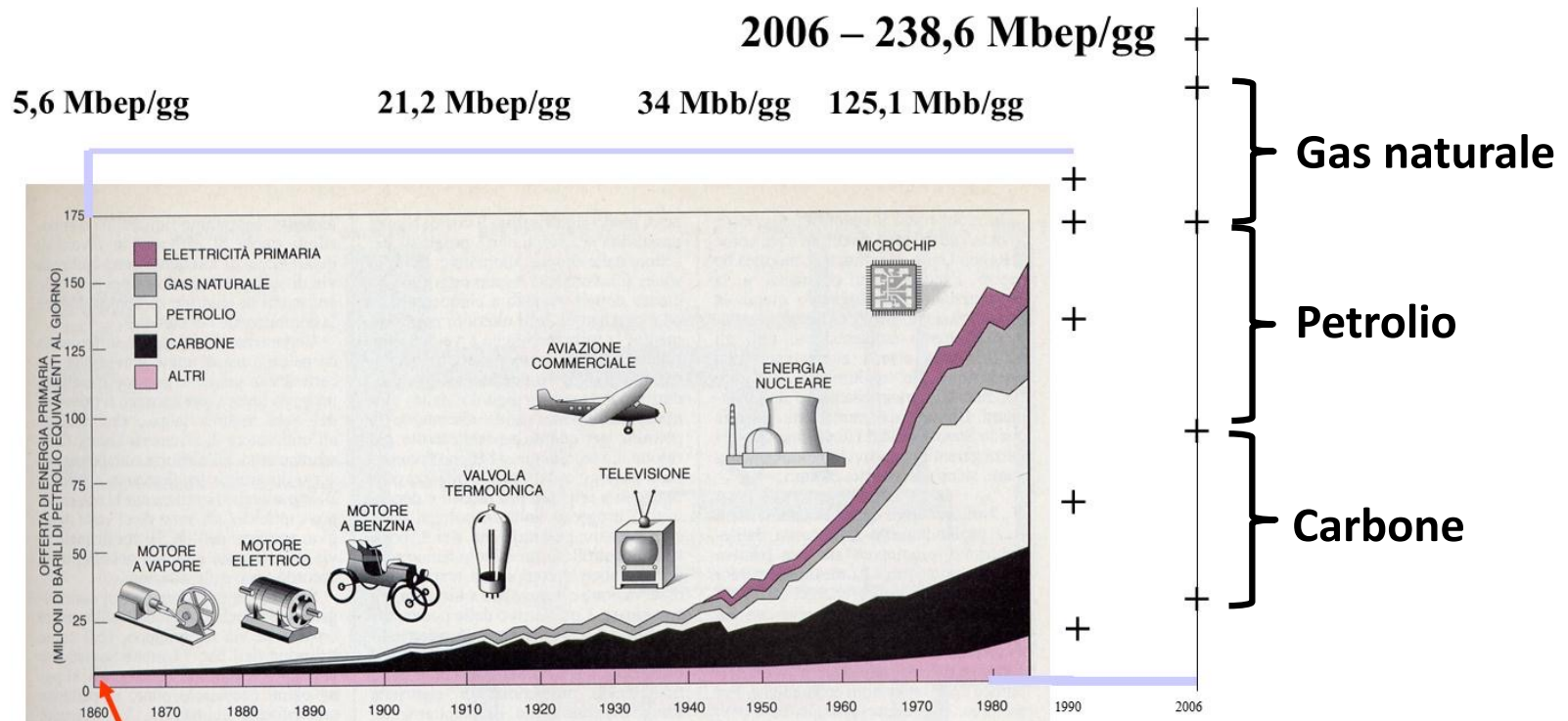


Energy harvesting – physical principles

Luca Gammaitoni

NiPS Laboratory, University of Perugia

Energy use in history



Dal 1860 abbiamo cominciato ad utilizzare il petrolio come fonte alternativa al Sole

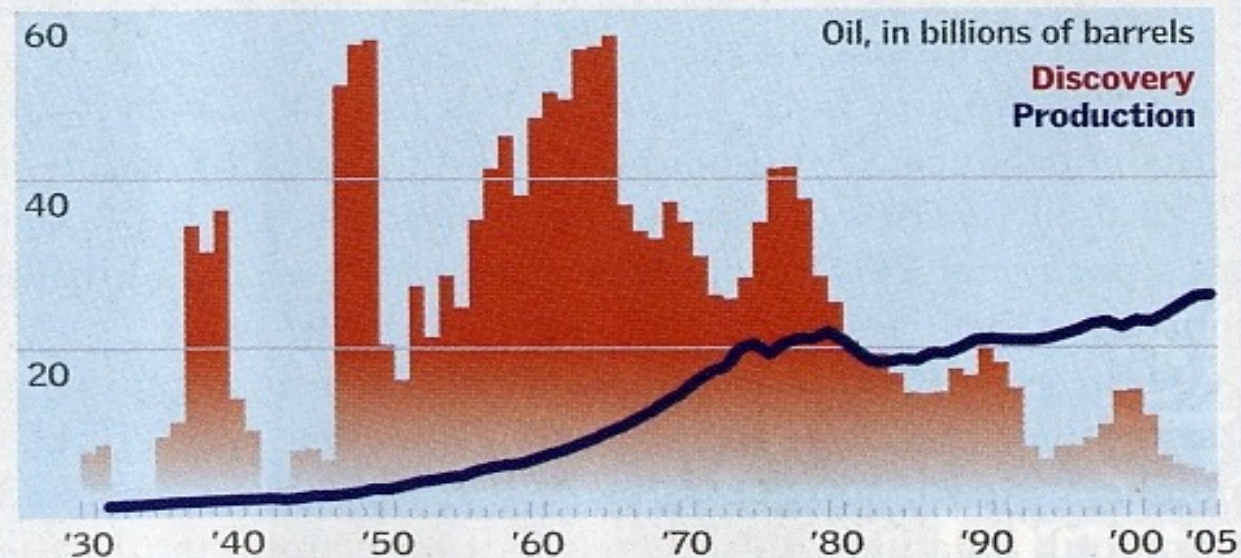
Il **barile equivalente di petrolio** o **barile di petrolio equivalente (BEP)**, in [inglese](#) *barrel of oil equivalent (boe)*, è un'[unità di misura](#) dell'[energia](#) che corrisponde all'energia approssimativa rilasciata dalla combustione di un [barile](#) di [petrolio greggio](#).

È stimata eguale a $6,1178632 \times 10^9 \text{ J}$ o circa 1,67 MWh.

Non-renewable sources: oil historical series

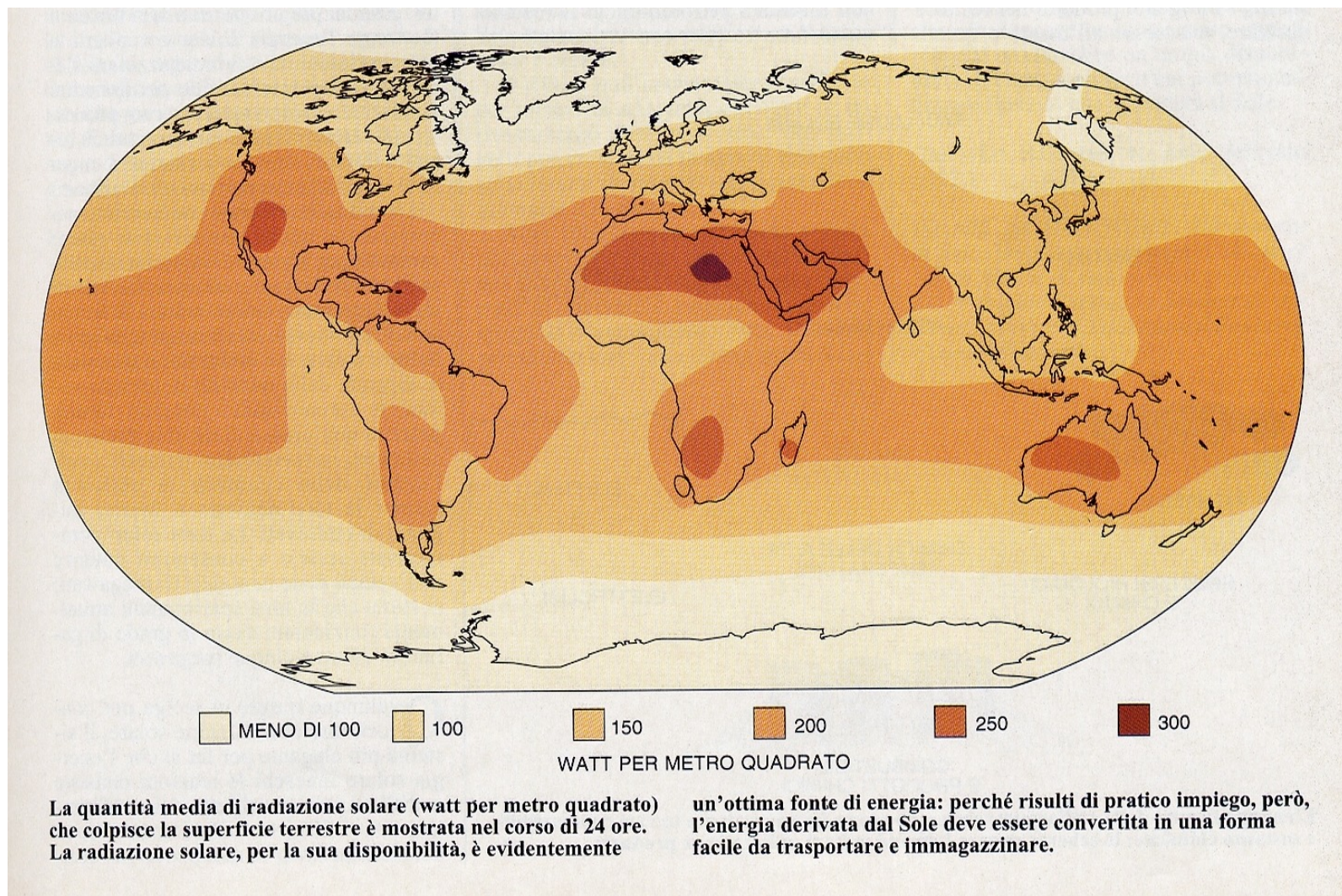
Getting scarce

Global oil finds peaked in 1964; the world now consumes five barrels of oil for every barrel discovered.

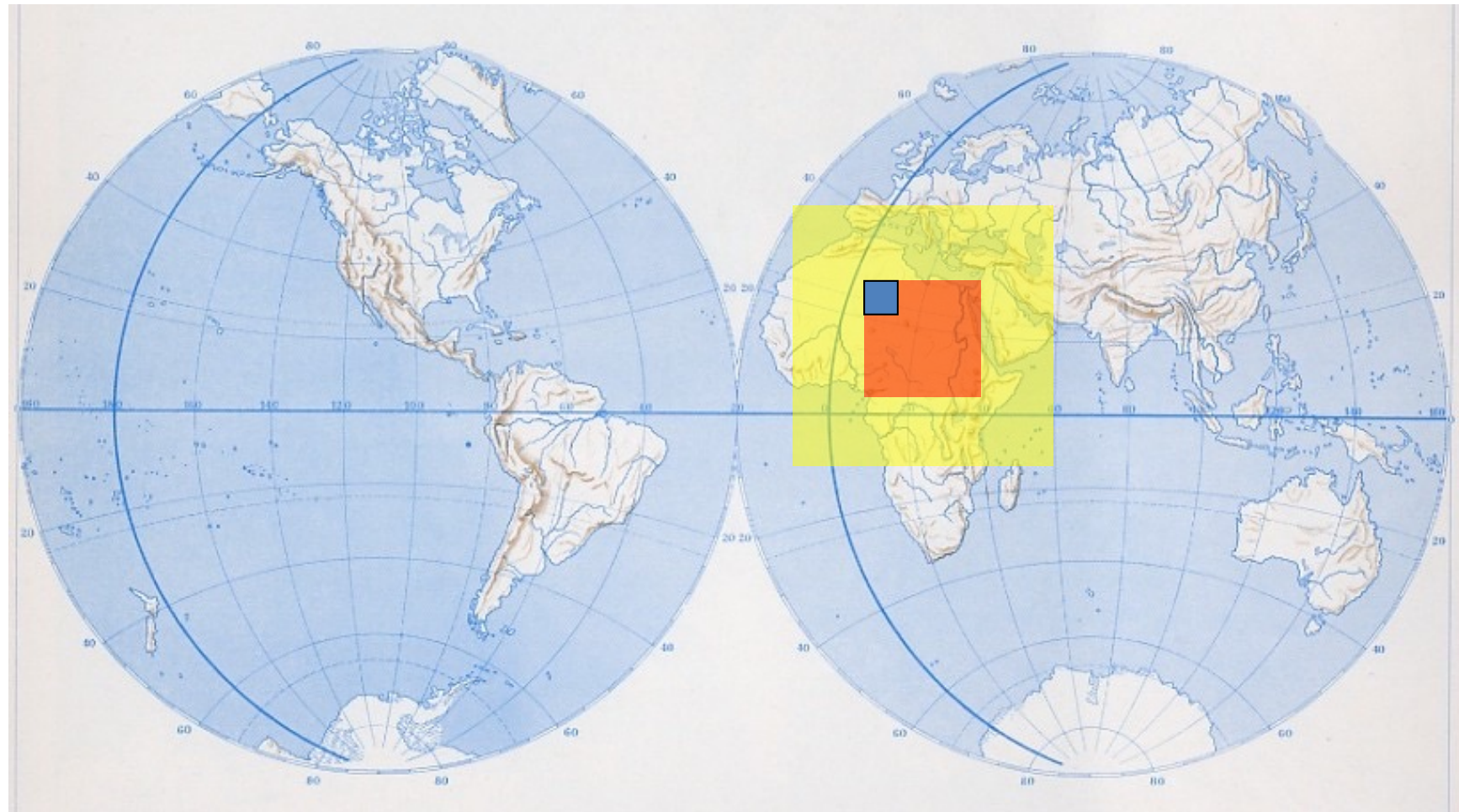


Source: ASPO International

Renewable source: solar power



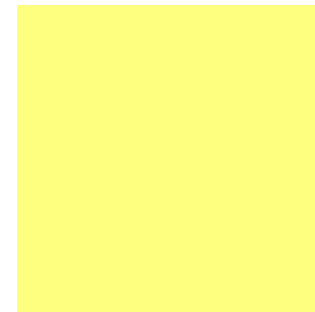
Oggi, può un mondo solare sostenere il fabbisogno energetico complessivo?
Il sole ci fornisce un'energia 15000 volte superiore a quella che consumiamo



■ Fotovoltaico



Eolico

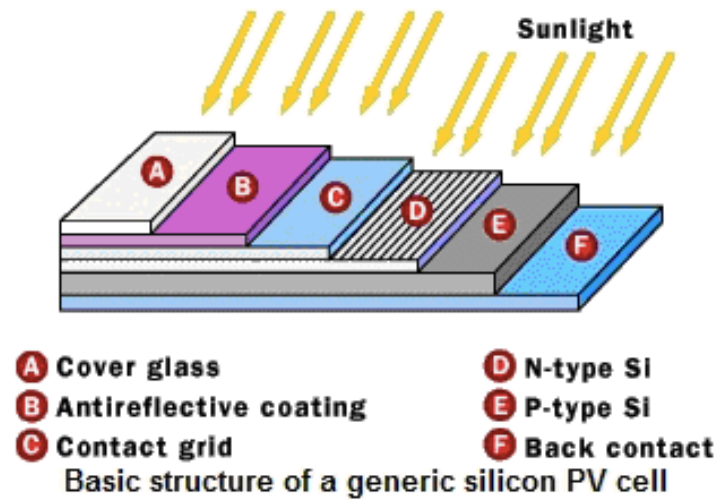
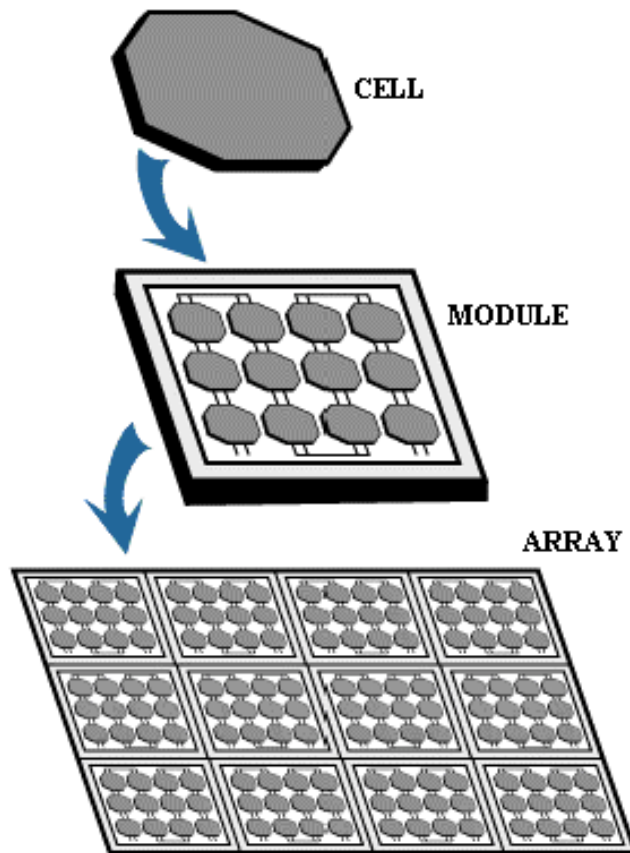


Biomasse

A photovoltaic system employs solar panels composed of a number of solar cells to supply usable solar power.

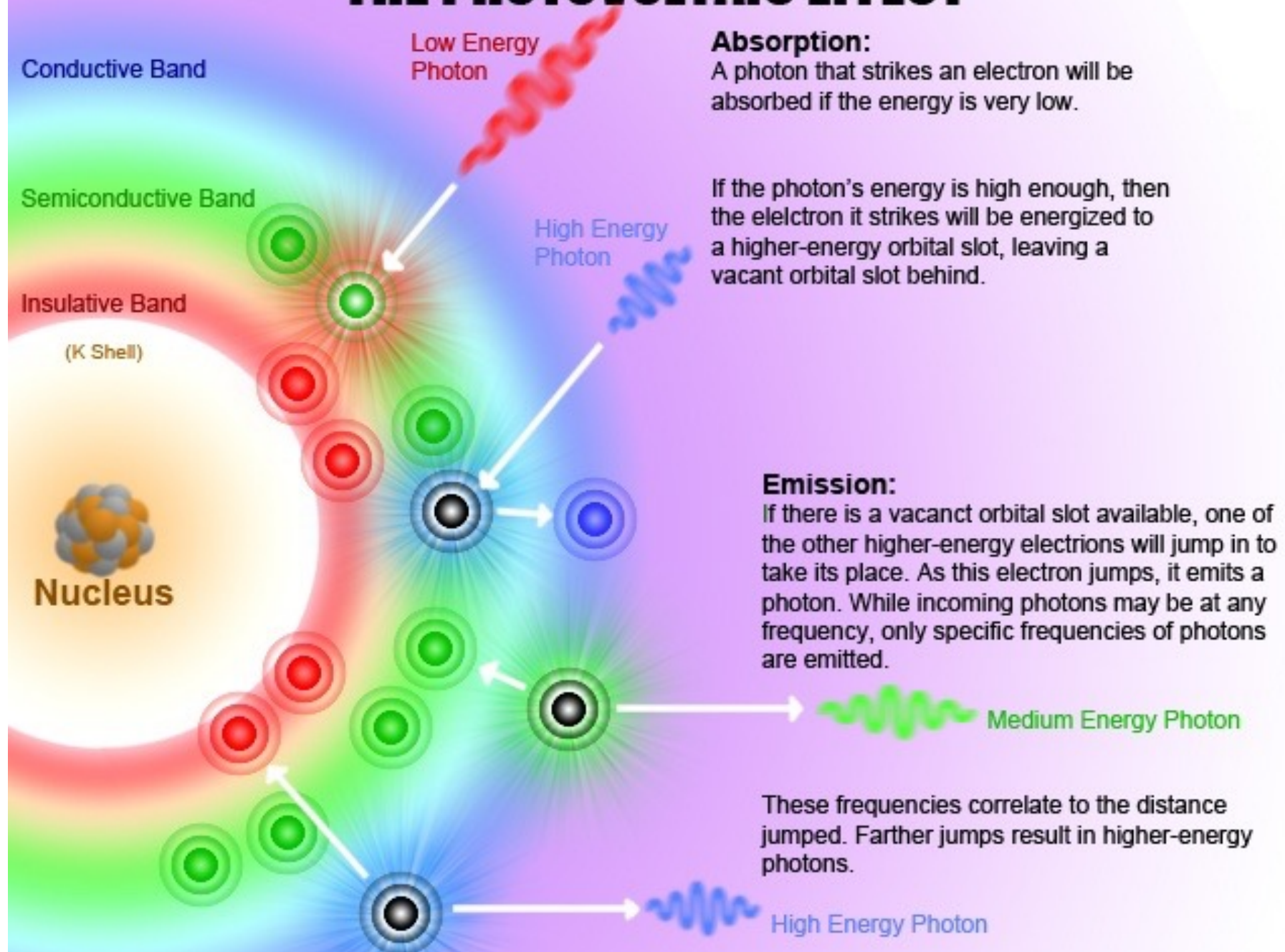


Photovoltaics (PV) is the name of a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect.

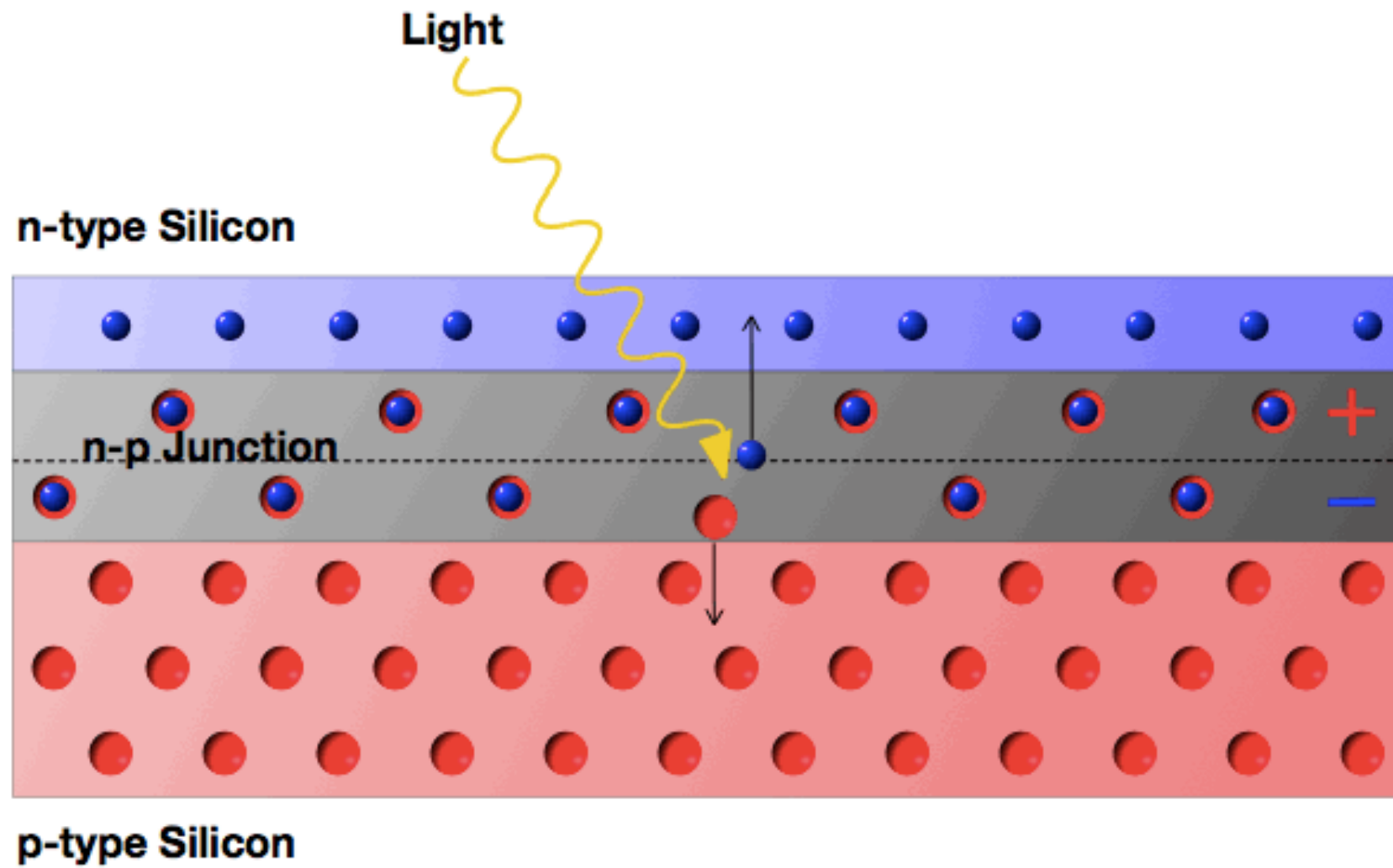


Photovoltaics (PV) is the name of a method of converting solar energy into direct current electricity using semiconducting materials that exhibit the photovoltaic effect.

THE PHOTOVOLTAIC EFFECT

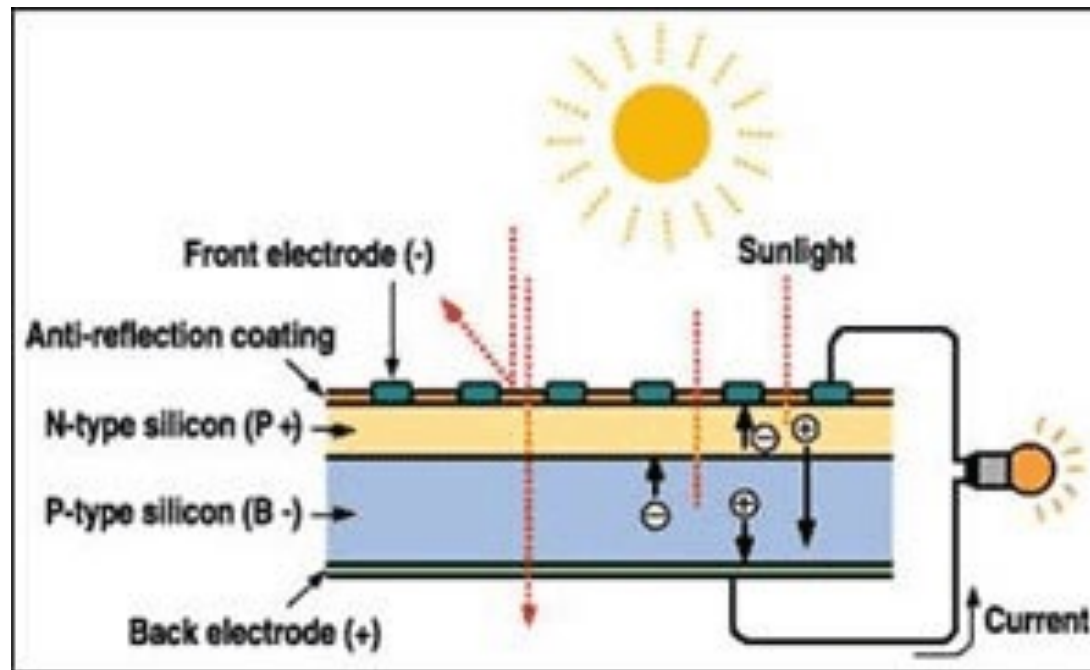


p-n junction

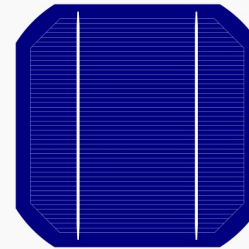


This voltage difference is typically in the range of **0.5V** for as long as the cell is in sunlight. If you short-circuit the upper and lower layer a current runs of about **3 Amps**.

If you arrange sufficient cells in series, the result is a PV module or PV panel. Let's say 36 cells in series produce $36 \times 0.5V = \mathbf{18V}$ at 3 Amps = **54Watts**.



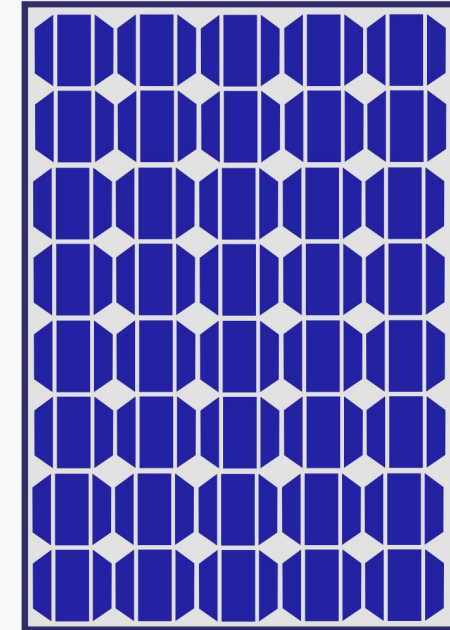
From a solar cell to a PV System



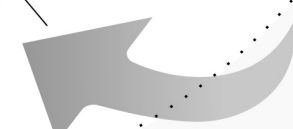
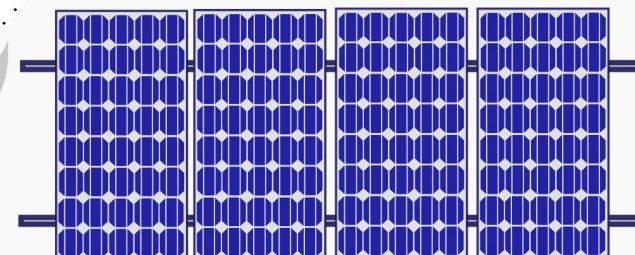
Solar Cell



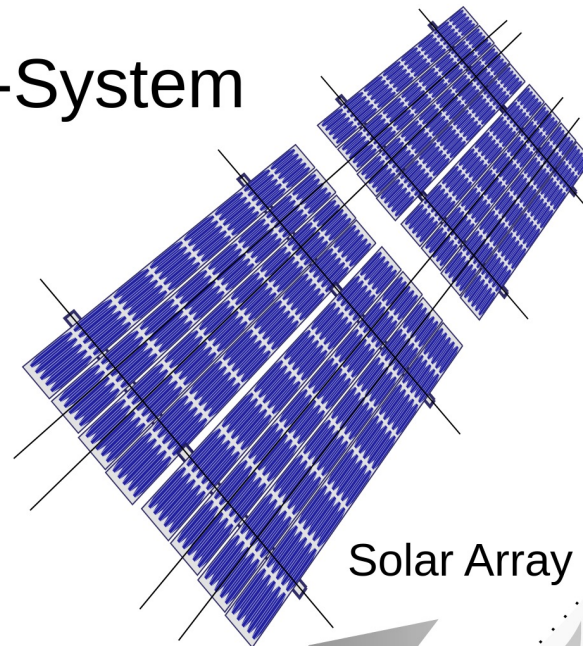
Solar Module



Solar Panel



Solar Array



PV-System

Electricity Meter

AC Isolator

Fusebox

Inverter

Battery

Charge Controller

Generation Meter

DC Isolator

Cabling

Mounting

Tracking System

Quanta energia si può ottenere?

In generale, l'andamento della produzione media segue la classica curva a campana, come nel caso delle curve riportate in figura 1, ricavate per un impianto da 3 kW ubicato a Firenze, orientato a Sud, con inclinazione di 30° e privo di ombreggiamenti rilevanti.

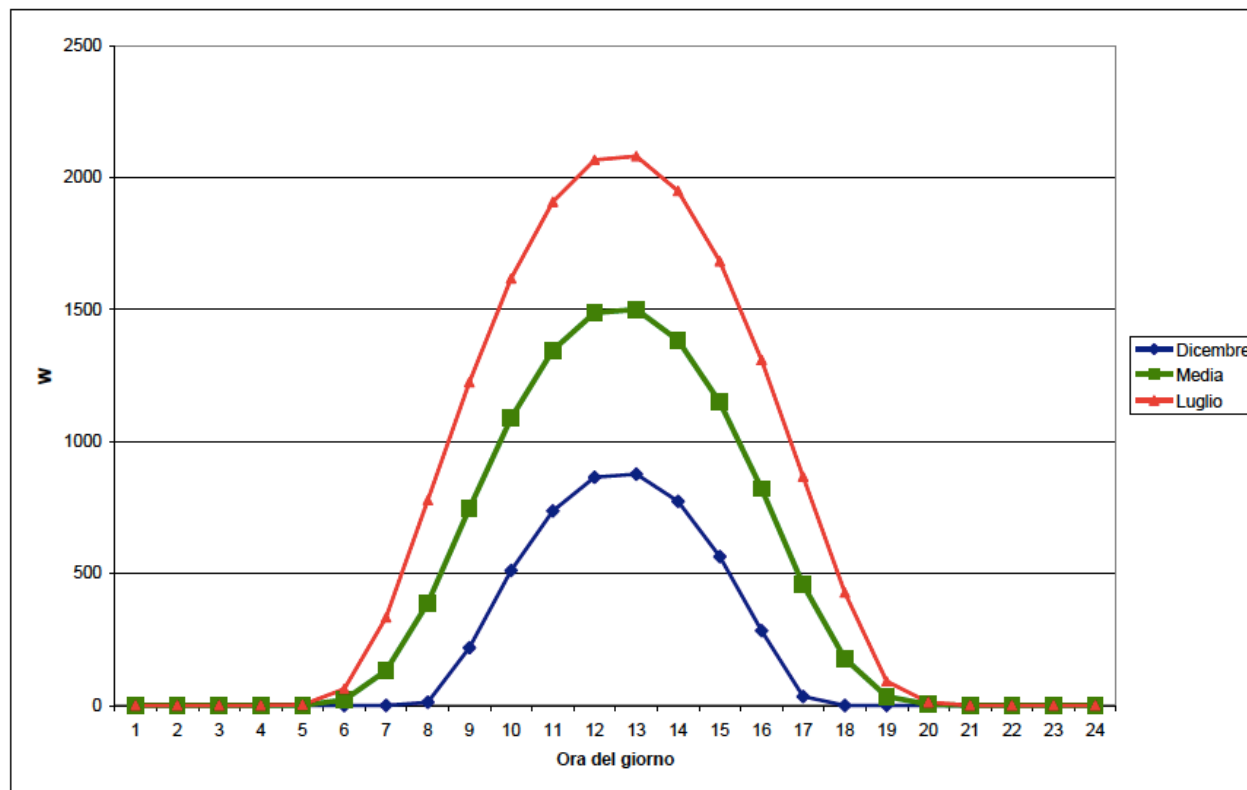


Figura 1 – Andamento giornaliero della potenza media prodotta da un impianto fotovoltaico di 3 kW ubicato a Firenze (dati forniti dal programma SunSim)

Quanta energia serve?

Apparecchio	Potenza assorbita [W]		Durata [minuti]		Utilizzi / giorno	Energia media giornaliera [kWh]
	Intervallo	Media	Intervallo	Media		
Lavabiancheria	650÷1000	825	60÷110	85	1,0	1,17
Lavastoviglie	450÷750	600	70÷130	100	1,0	1,00
Ferro da stiro	700÷1000	850	30÷60	45	0,5	0,32
Aspirapolvere	800÷1200	1000	10÷30	20	1	0,33
Computer, stampanti, ecc.	200÷300	250	-	200	1	0,83
Totale						3,65

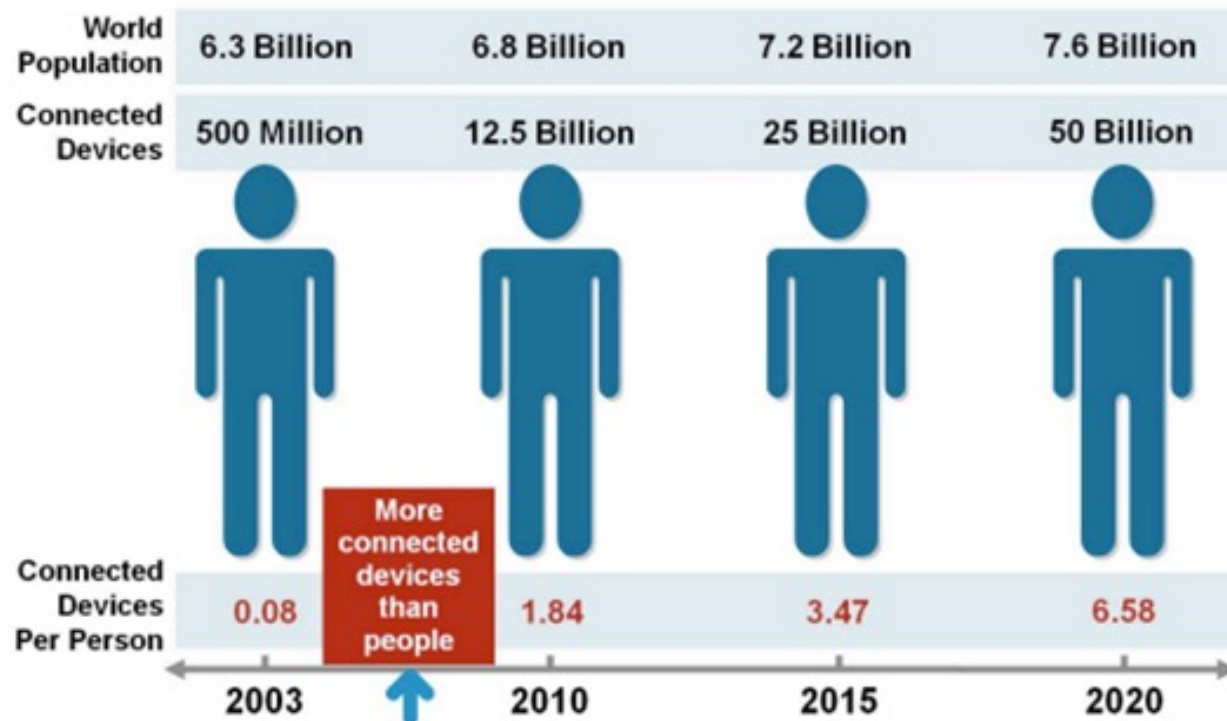
Tabella 1 – Valori medi di consumo relativi ai carichi temporalmente trasferibili

Not only energy for appliances but also energy for
networked, interconnected
mobile devices

April 4,
2005



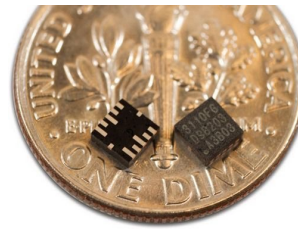
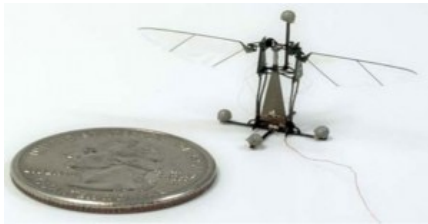
March 13,
2013



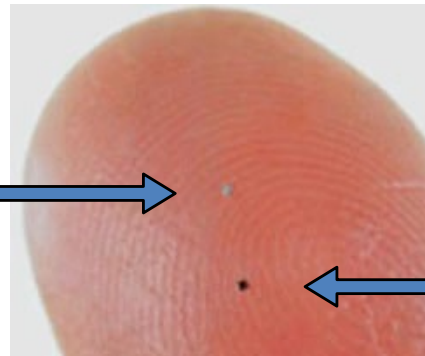
Source: Cisco IBSG, April 2011

Devices of different nature and dimensions

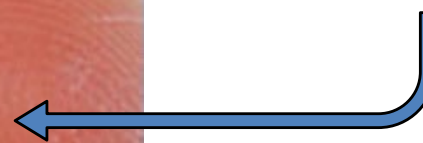
Autonomous microdevices, micro robots, wireless sensor networks

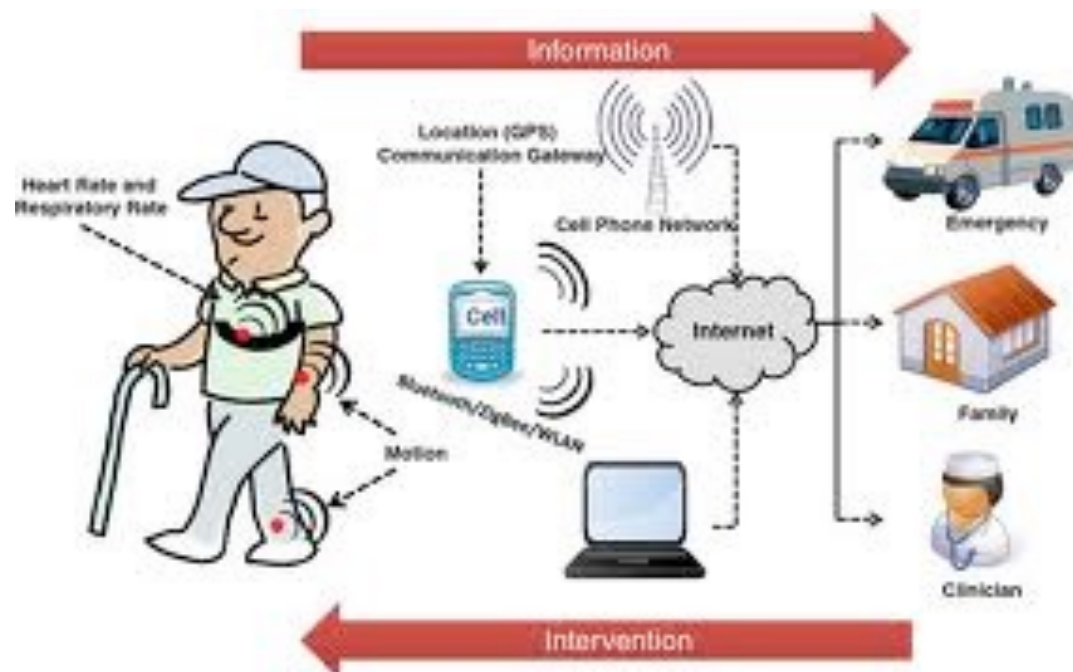
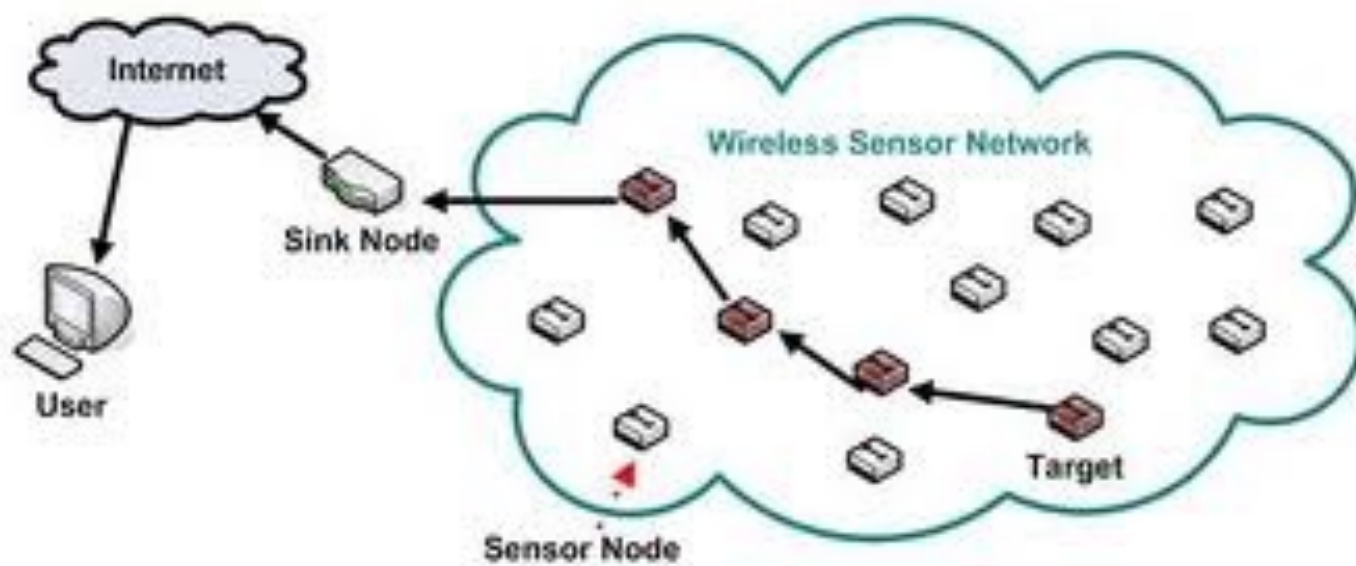


dust particle



computer





Un mondo interconnesso dove l'uomo è uno dei soggetti



Eco sistema naturale



Eco sistema

Ogni ecosistema è costituito da una comunità di organismi viventi che interagiscono tra di loro; una comunità è a sua volta l'insieme di più popolazioni costituite ognuna da organismi della stessa specie.

L'insieme delle popolazioni e cioè la comunità, interagisce anche con la componente abiotica formando l'ecosistema, nel quale si vengono a creare delle interazioni reciproche in un equilibrio dinamico.

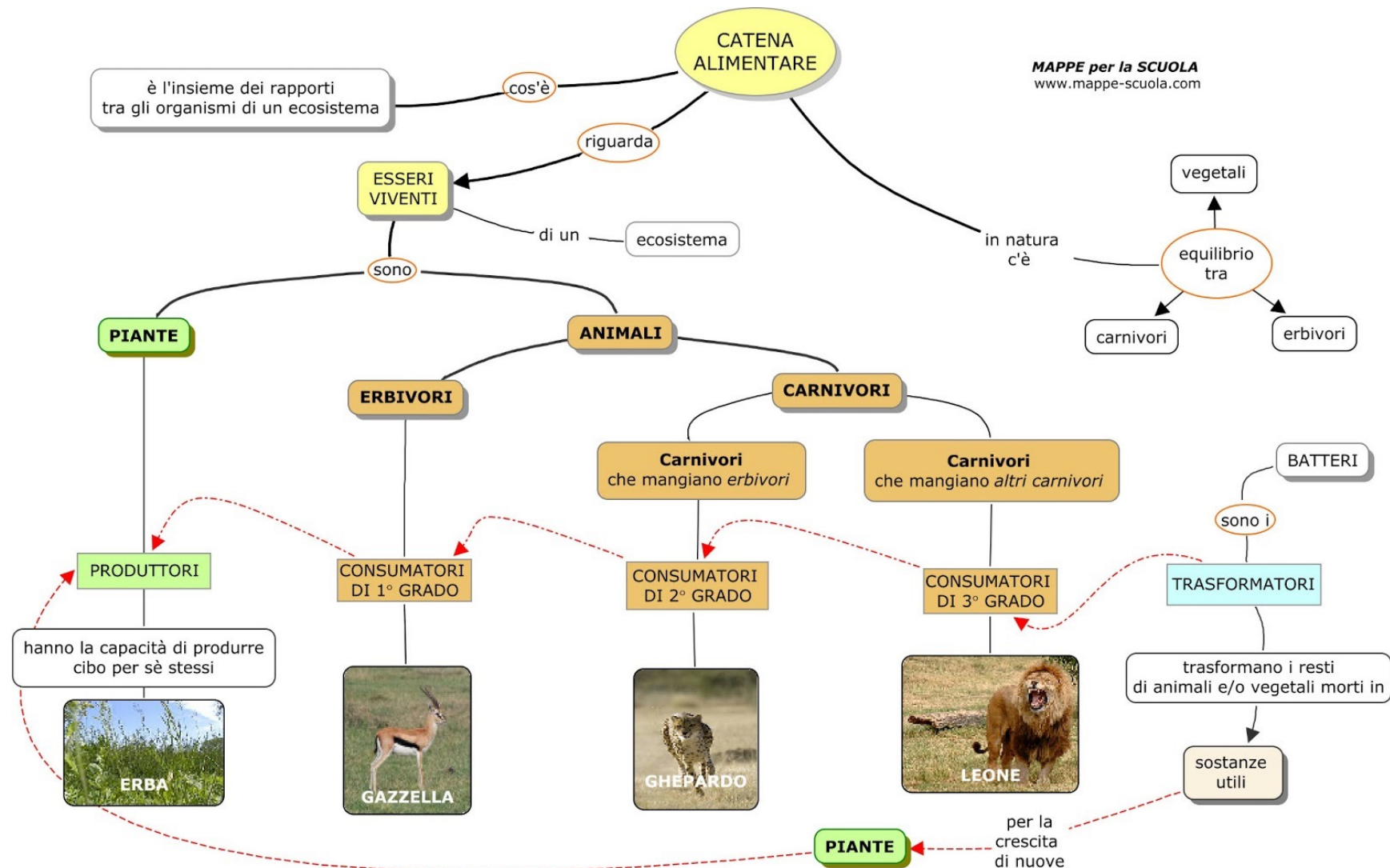
Un ecosistema viene definito come un sistema aperto, con struttura e funzione caratteristica determinata da:

- flusso di [energia](#);
- circolazione di materia tra componente [biotica e abiotica](#).

Gli ecosistemi presentano quattro caratteristiche comuni:

- sono sistemi aperti;^[2]
- sono strutture interconnesse con altri ecosistemi;
- tendono a raggiungere e a mantenere nel tempo un certo equilibrio dinamico e quindi una particolare stabilità mutevole;
- sono sempre formati da una componente [abiotica e da una componente biotica](#).

Il problema dell'approvvigionamento energetico

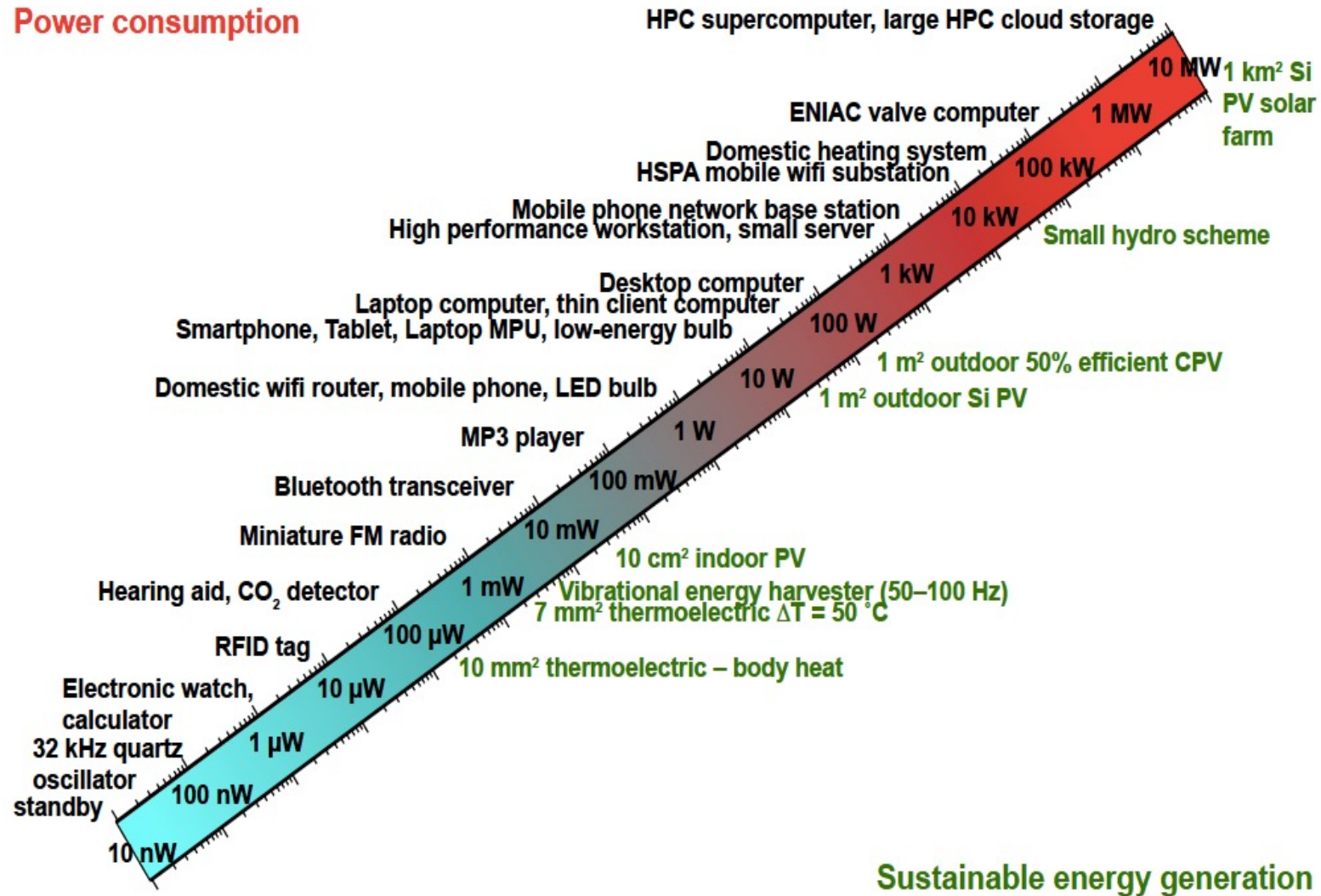


Eco Sistema ibrido: natural + artificiale

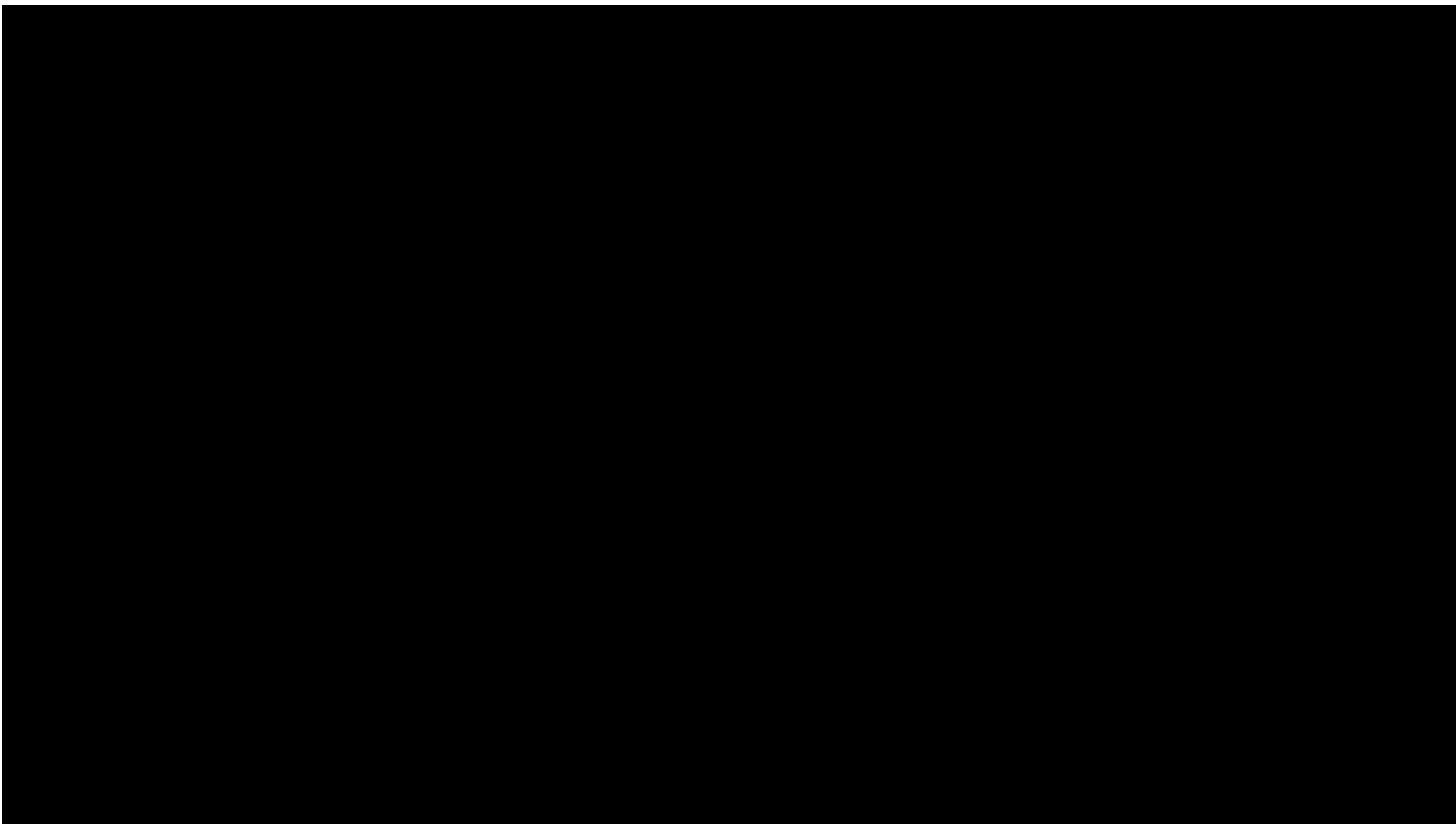


ICT energy requirements

Power consumption

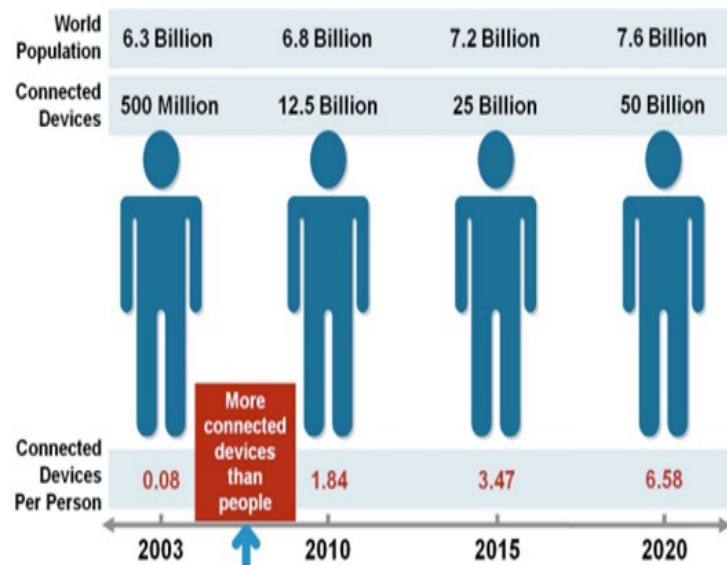


Source: D. Paul, ICT-Energy Research Agenda, 2015



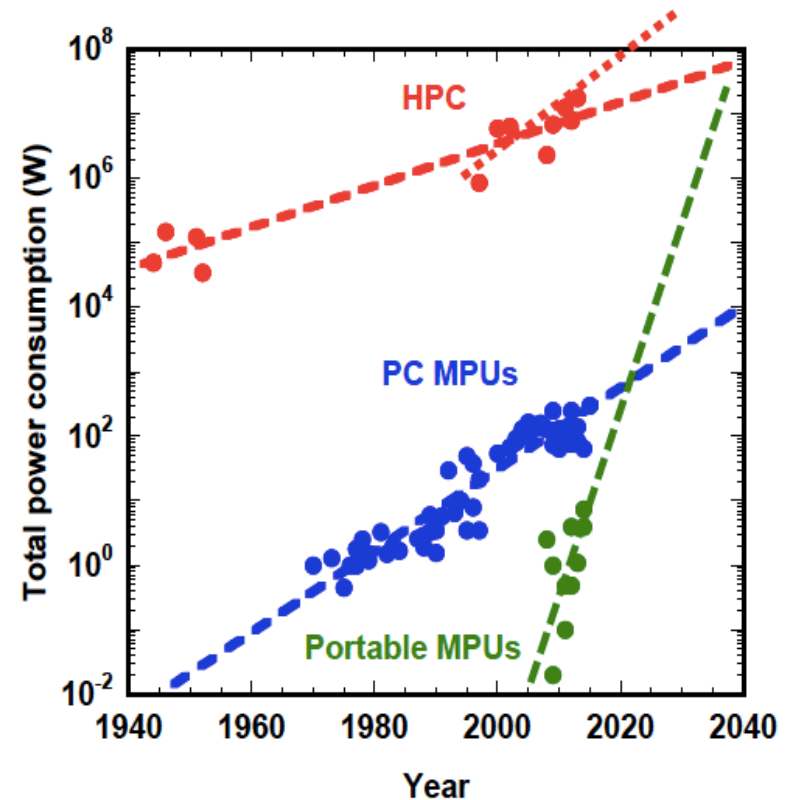
Fact

Mobile computing is growing exponentially. The so called Internet of Things scenario requires reliable low-power devices capable of computing and communication.



Source: Cisco IBSG, April 2011

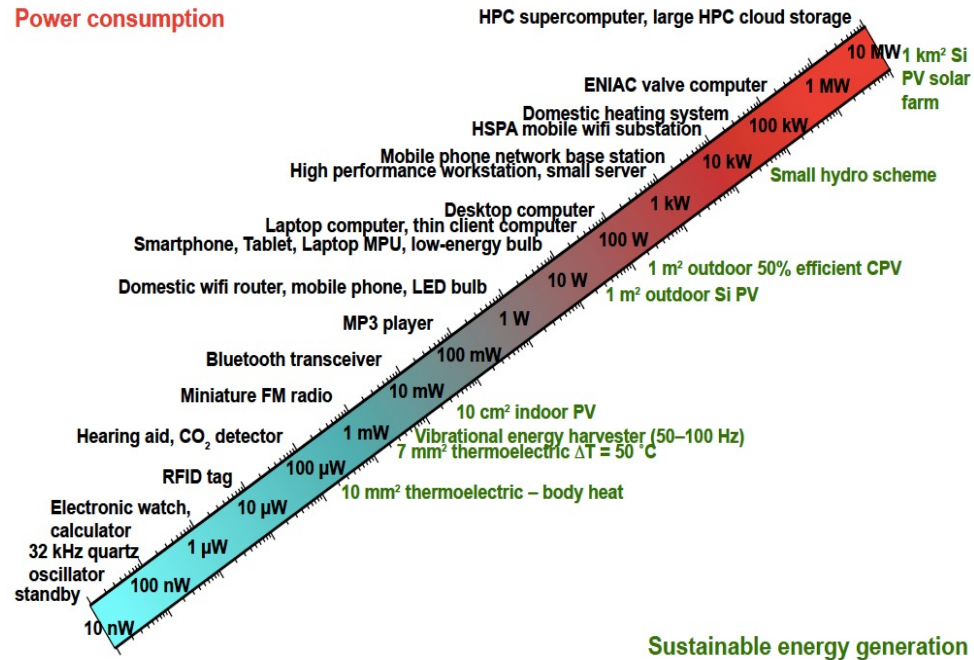
Need for autonomous power



Source: D. Paul, ICT-Energy Research Agenda, 2015

Energy required to operate the portable devices

Power consumption



Energy available from portable sources (energy harvesting)

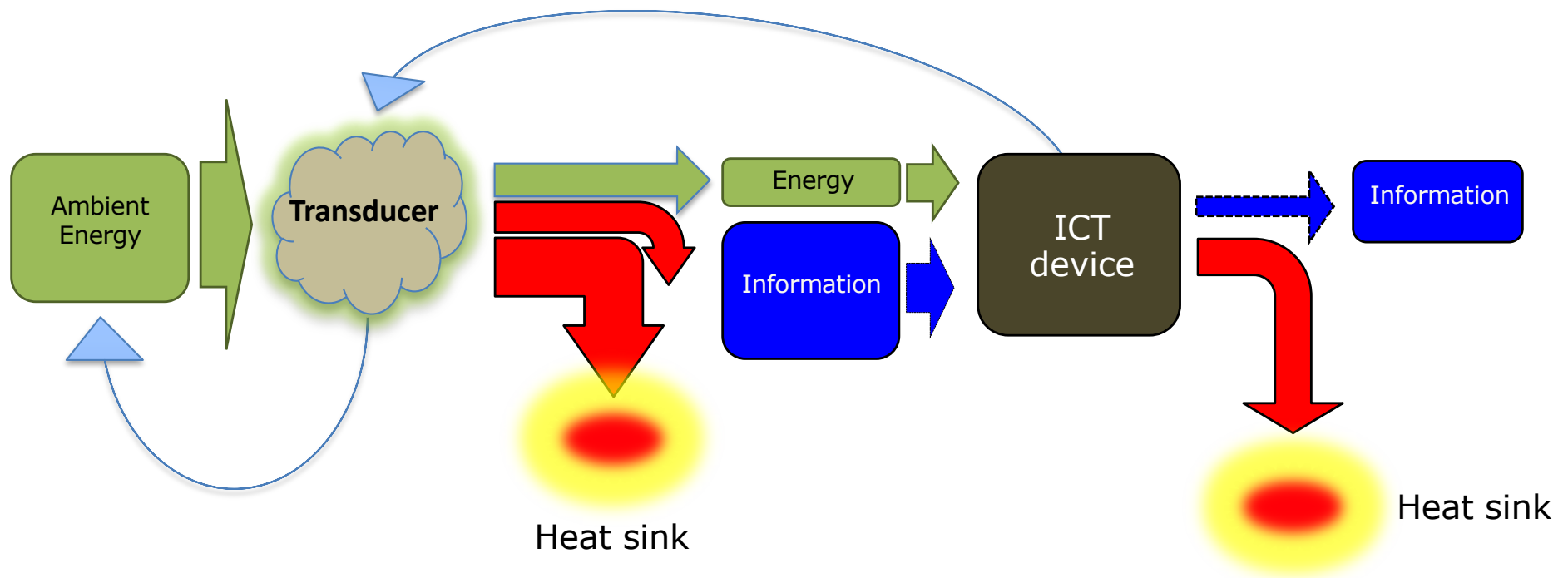
Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009.
EH: Energy Harvesting; WSN: Wireless Sensors Network

The device powering issue:

- 1) How much energy is needed to power a device ?
- 2) Where does the device get the needed energy ?

We consider devices at MEMS scale and below

We consider “ICT devices”: i.e. devices mainly devoted to computing task



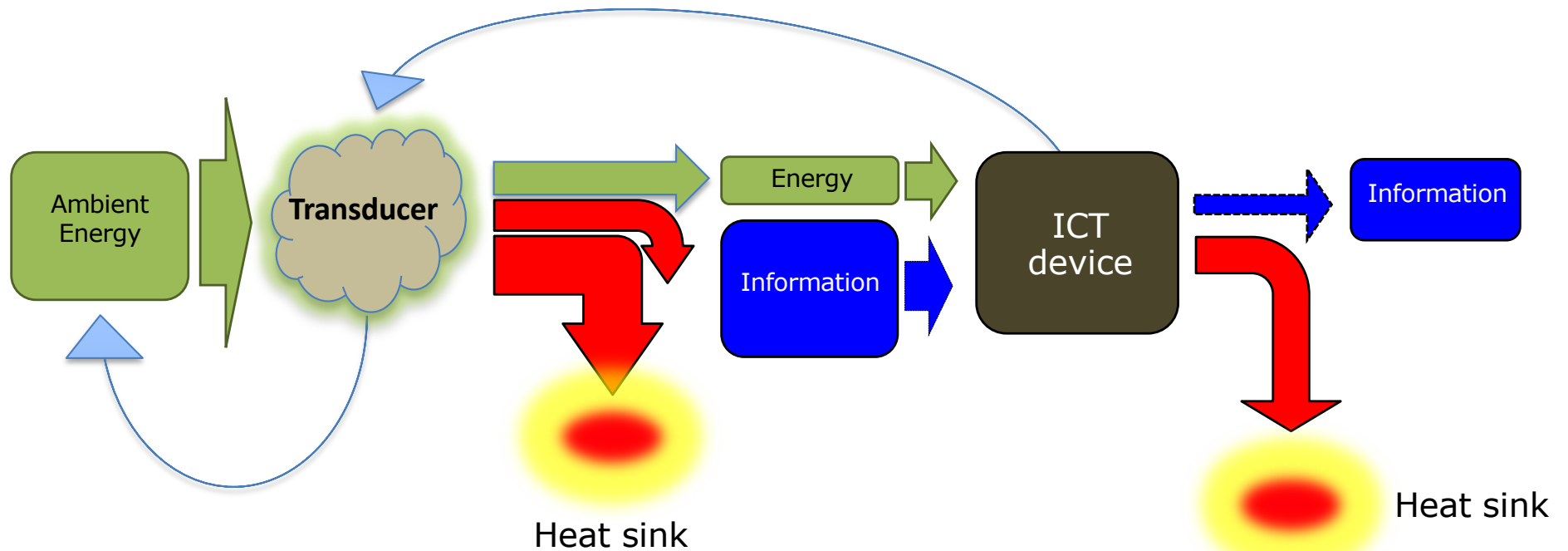
An **ICT device** is an info-thermal machine that inputs **information** and **energy** (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

Some interesting questions:

Why all the energy ends up in heat?

What does it mean “energy dissipation”?

Can be avoided?



We need a physical model...

Two physical systems:

They transform energy

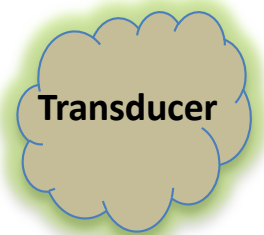
They have many d.o.f. (presence of fluctuations)

They are operated in a changing environment

~~Thermodynamics~~

~~Statistical mechanics~~

Non-equilibrium statistical mechanics

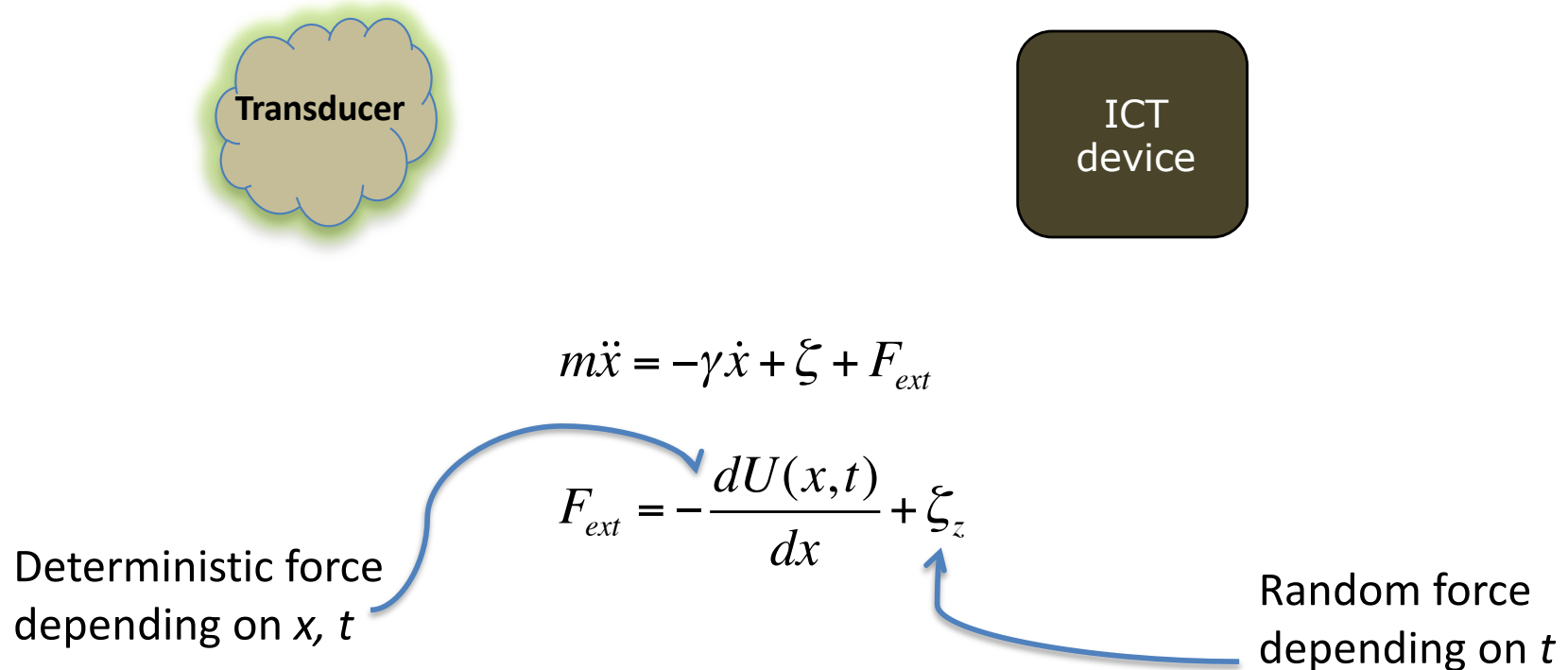


In this framework we can describe the device behavior in terms of few relevant d.o.f. via a procedure called “adiabatic elimination” or “coarse graining approach”: we exchange the dynamics of a *not small isolated system* with *small not isolated system*.

Let's see an example...

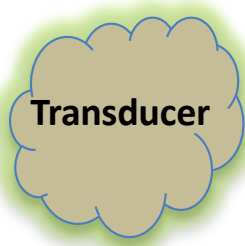
Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach



If $F_{ext} \gg \zeta$ then the thermal noise contribution can be ignored

$$m\ddot{x} = -\frac{dU(x,t)}{dx} - \gamma\dot{x} + \zeta_z$$



Langevin equation approach

$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \xi_z - \gamma\dot{x} + \xi$$



This is a stochastic dynamics whose solution $x(t)$ appears like



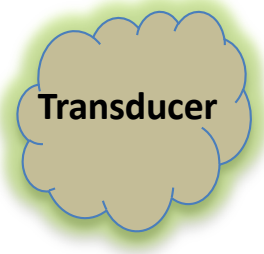
Probability density $P(x,t)$.

$P(x,t)dx$ represents the probability for the observable x to be in $(x, x+dx)$.

$P(x,t)$ is a deterministic quantity and its time evolution of can be described in terms of the associated Fokker-Planck equation.

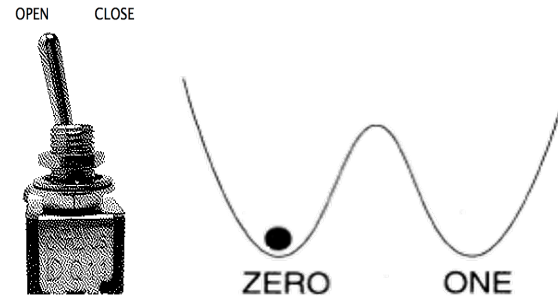
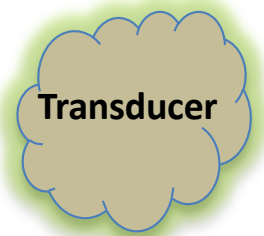
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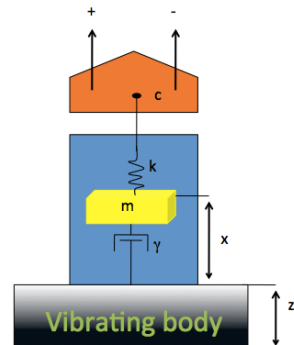


(example from a digital binary switch)

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} + F_{sw} + \zeta$$
$$\langle \zeta(t) \zeta(0) \rangle = 2 K_B T \gamma \delta(t)$$

Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach



(example from vibration harvester)

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - c(x, V) + \zeta_z + \zeta$$

$$\dot{V} = F(\dot{x}, V)$$

The device powering issue:

- 1) How much energy is needed to power a device ?
- 2) Where does the device get the needed energy ?

