Quantum effects in signal transduction biology: perspectives for 21st century Nanoelectronics

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Quantum Effects

$H\Psi=E\Psi$

Nanoelectronics

Signal Transduction Biology

Quantum Mechanics

1970s: Quantum Chromodynamics

1900: Plank's Law

1940s: Quantum Electrodynamics

1905: Einstein's Photoelectric Effect

1928: Dirac Relativistic Equation

1913: Bohr's Atomic Model

1926: Fermi-Dirac statistics

1926: Schrödinger Equation

1924: De Broglie's Wave-particle Duality

1925: Pauli Exclusion Principle

NEW QT

1925: Heisenberg's Uncertainty Principle

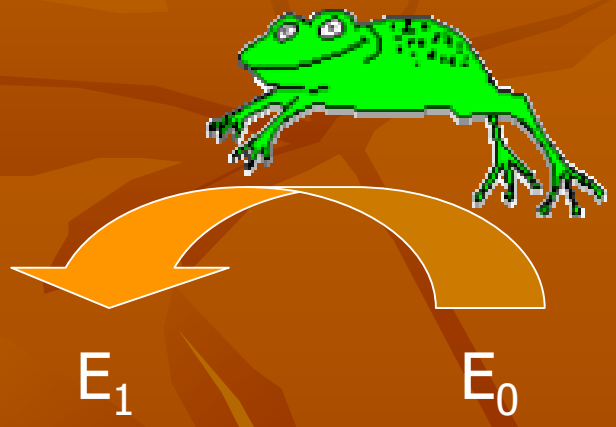
OLD QT

Quantum effects: what are they?

- Physical quantities (energy, momentum, etc.) assume discrete values rather than being continuous
- Uncertainty principle:

  $\Delta x \Delta p \geq h/2\pi$
- Wave-particle duality:

  microscopic objects may behave like waves or particles
- Entanglement:



Quantum effects (microscopic objects)

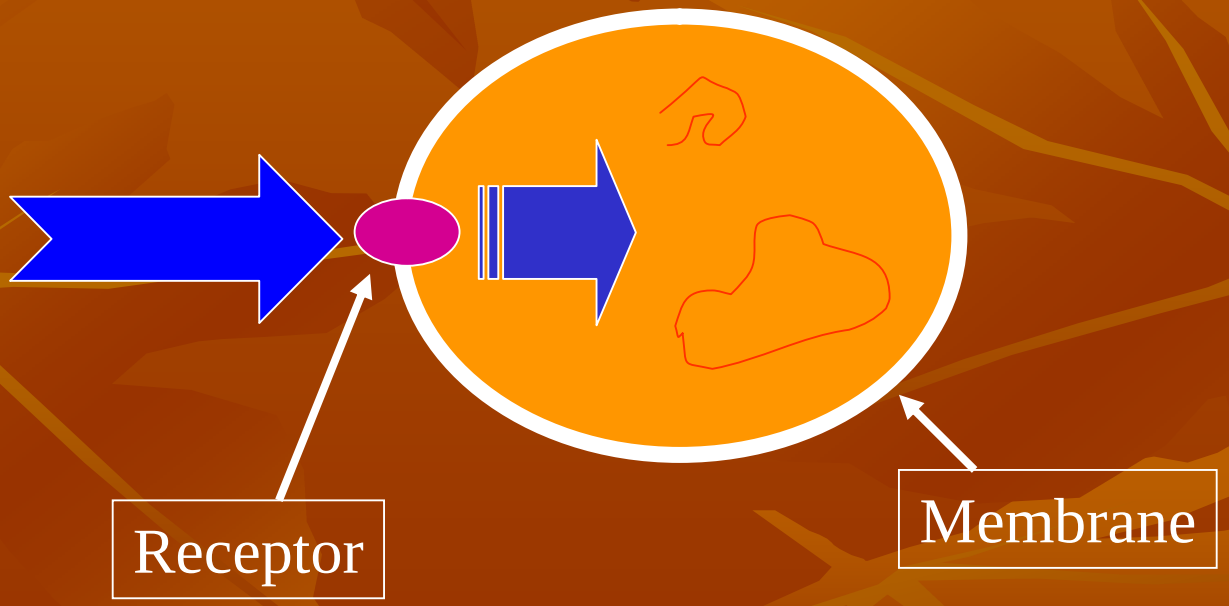
- Elementary particles (Particle Physics)
- Nuclei (Nuclear Physics)
- Atoms (Atomic Physics)
- Molecules (Chemistry, Biology)
- Nanoparticles (Nanotechnology)

Applications

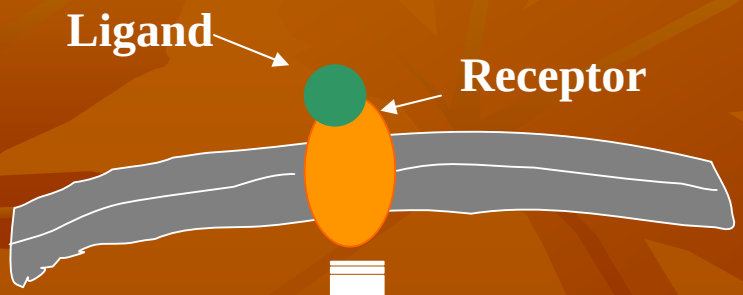
- Laser
- Transistor
- Electron Microscope
- Scanning Tunneling Microscope (STM)
- Magnetic Resonance Imaging (MRI)
- Superconductivity
- Teleportation

Signal Transduction Biology

ST Biology is concerned with the transmission of extracellular signals into intracellular biological effects:



Signal Transduction in the Cell



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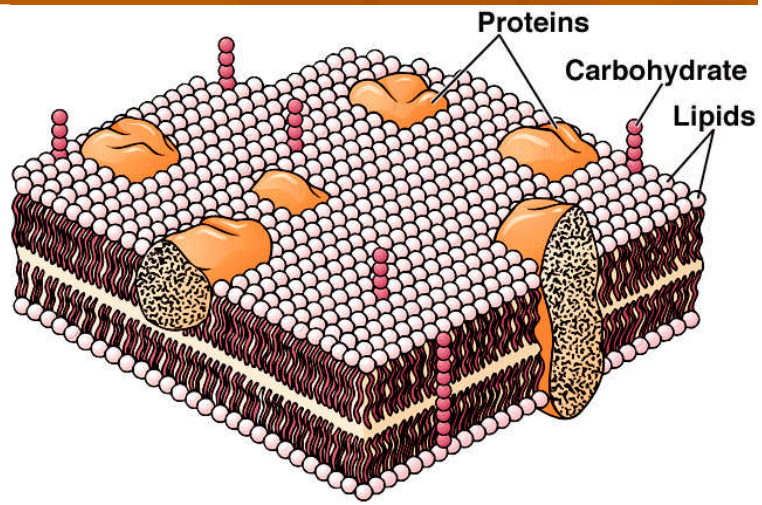
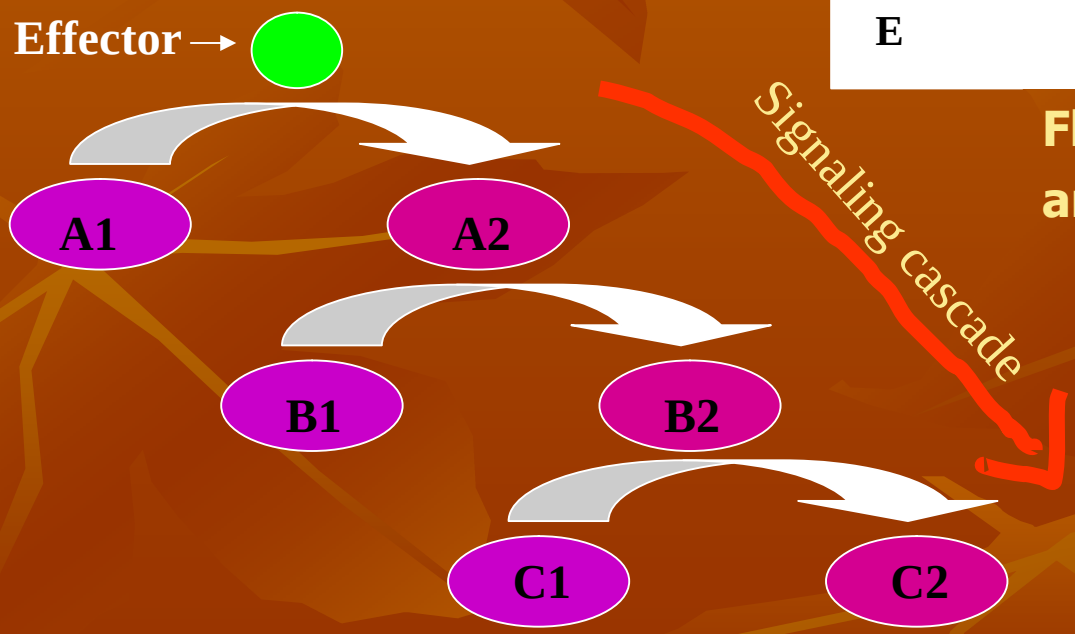


Fluid Mosaic Model by Singer and Nicolson (1972)



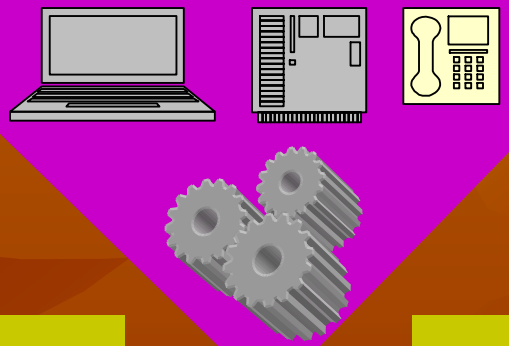
Receptors on the cell's surface

- Ion channel-linked receptors

  Nobel Prize 2003 for Chemistry awarded to MacKinnon (K^+ channel) and Agre (water channel – aquaporin)
- G-protein-linked receptors
- Enzyme-linked receptors

Nanoelectronics

Miniaturization of electronic devices and their components



Top-down approach

Bottom-up approach

Nanoelectronics

Atom-based bottom-up approach:

- Atom electronics (Eigler, Wada, et al.)

Molecular-based bottom-up approaches:

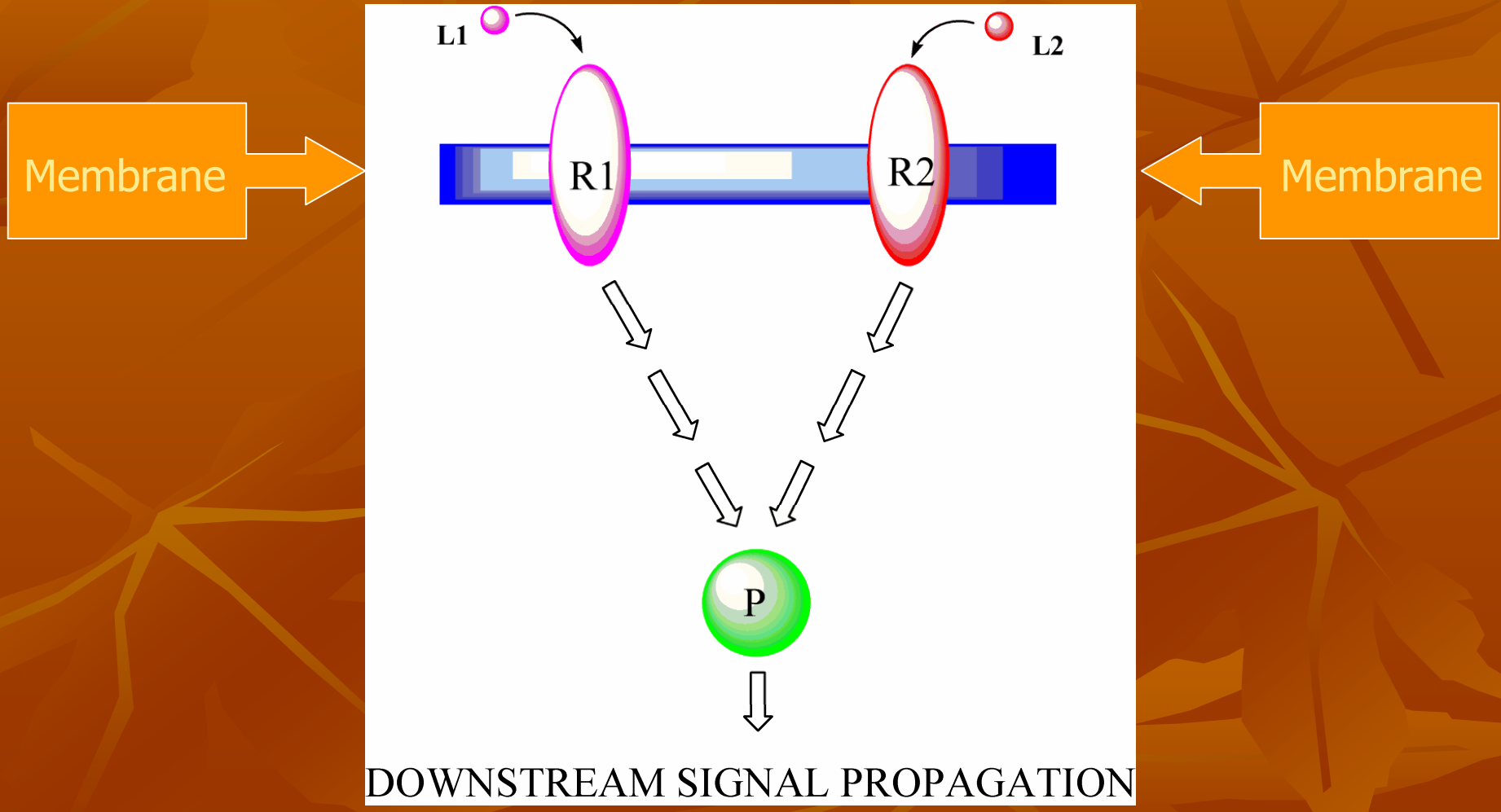
- Molecular electronics (Aviram-Ratner, 1974)
  synthetic molecular-scale devices (rectifiers, wires, switches, etc.)
- Biomolecular electronics (Birge, Nicolini, et al.)
  biomolecules (proteins, DNA, etc.) are the components of nanoscale devices

Is this enough?

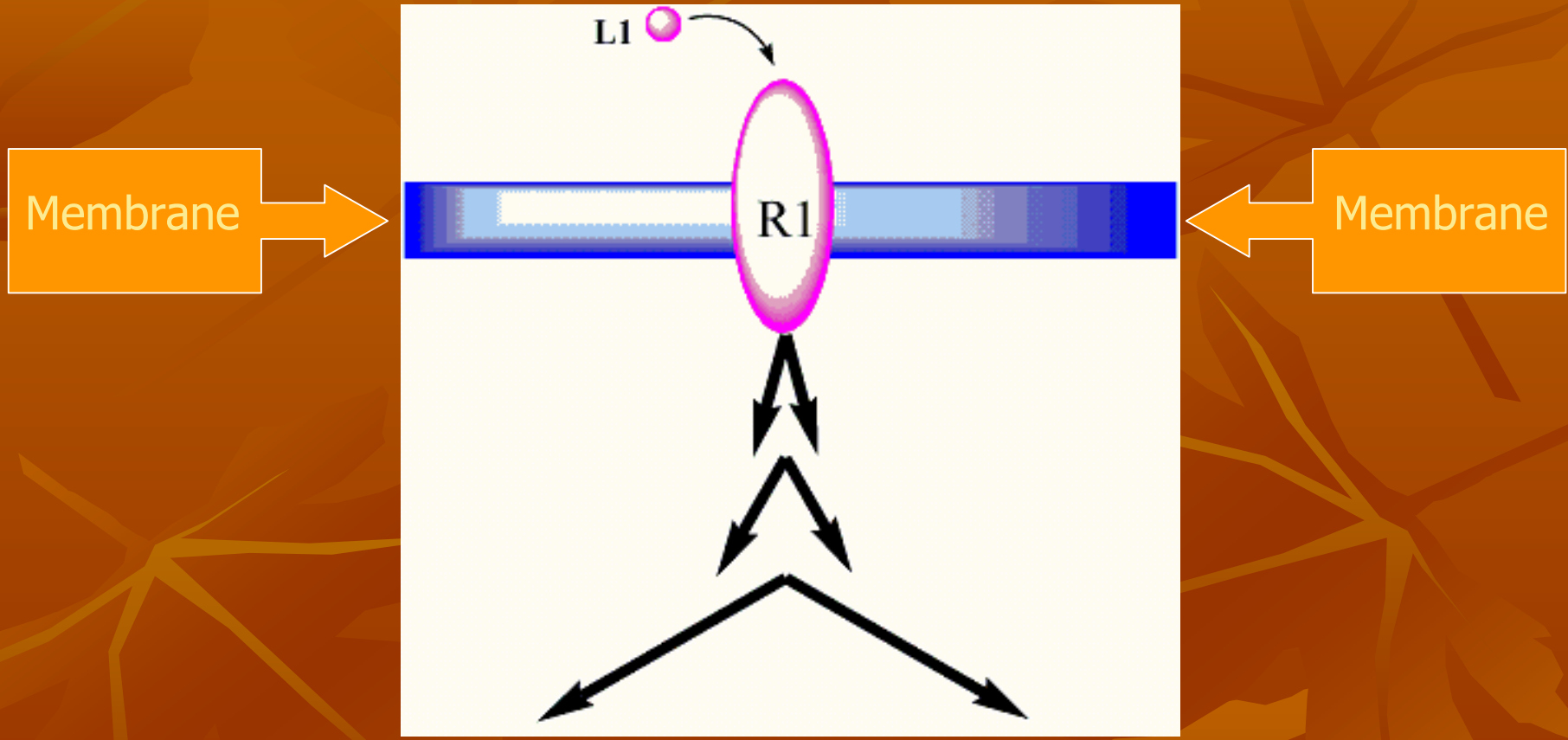
- Not only size but also functionality matters!
- Molecular components must work together and, hence, need to be interconnected with each other while keeping their own individuality (integration of components & signals)
- Interaction with the external world requires the amplification of signals (signal amplification)
- Thermodynamic and structural stability

Nature has already solved these complex problems!

Signal integration



Signal amplification

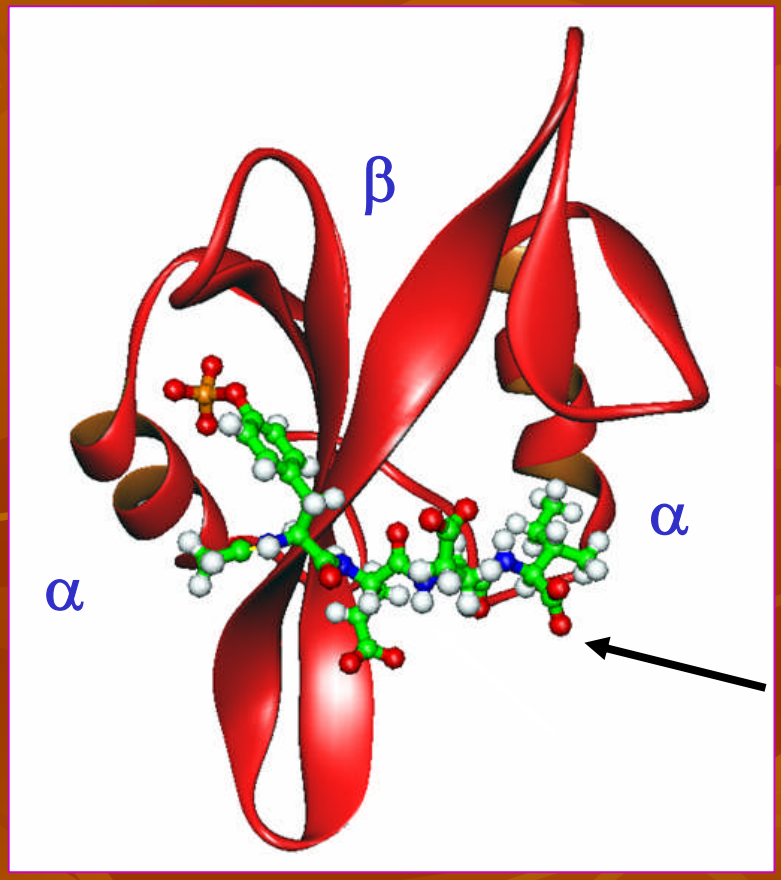


E.g. Visual transduction cascade:
Rhodopsin > ••• > 10^5 cGMP hydrolized molecules!!!

The SH2 domain in ST Biology

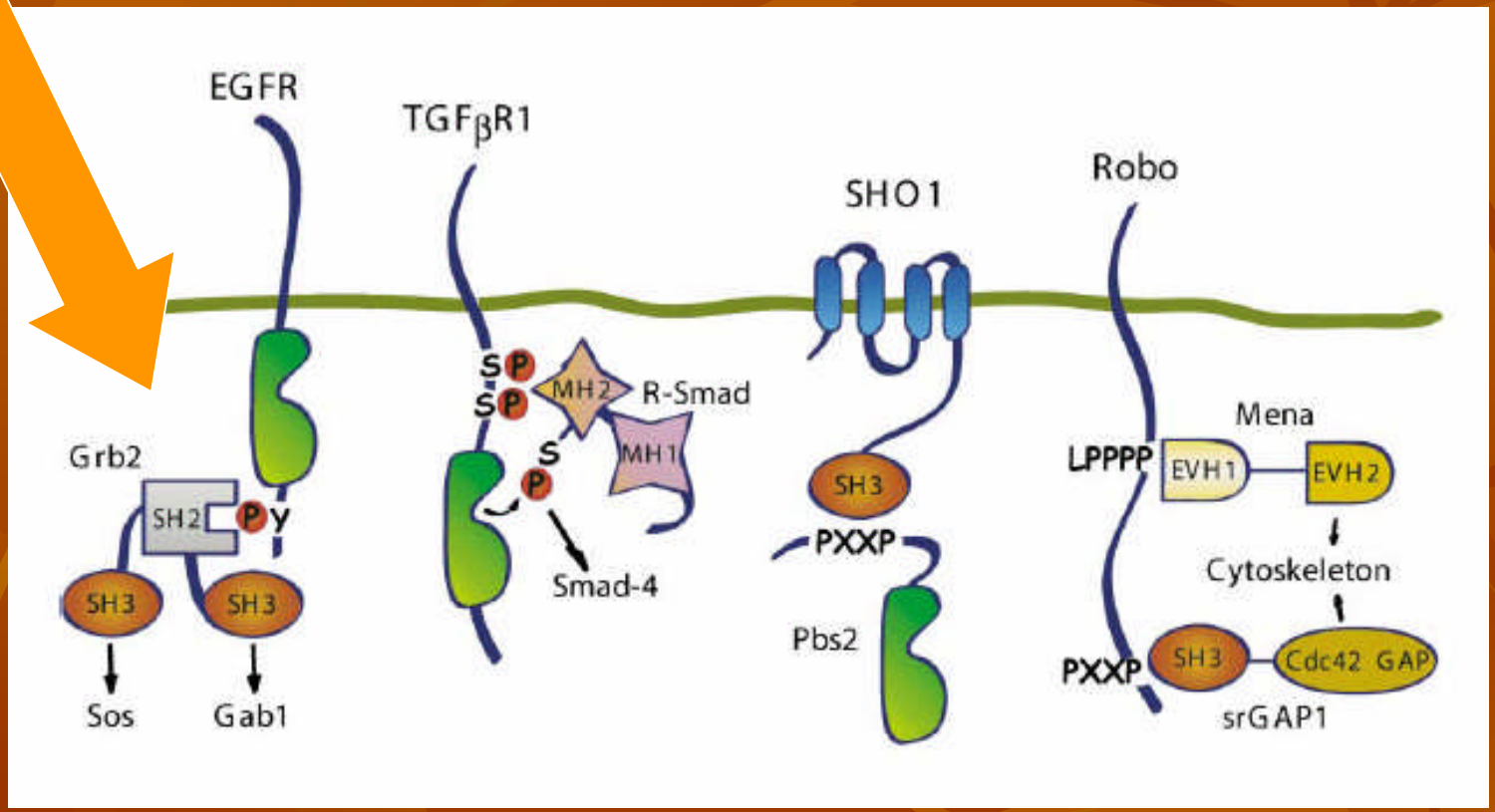
SH2 domain of p56-Lck Kinase

$\alpha/\beta/\alpha$ motif



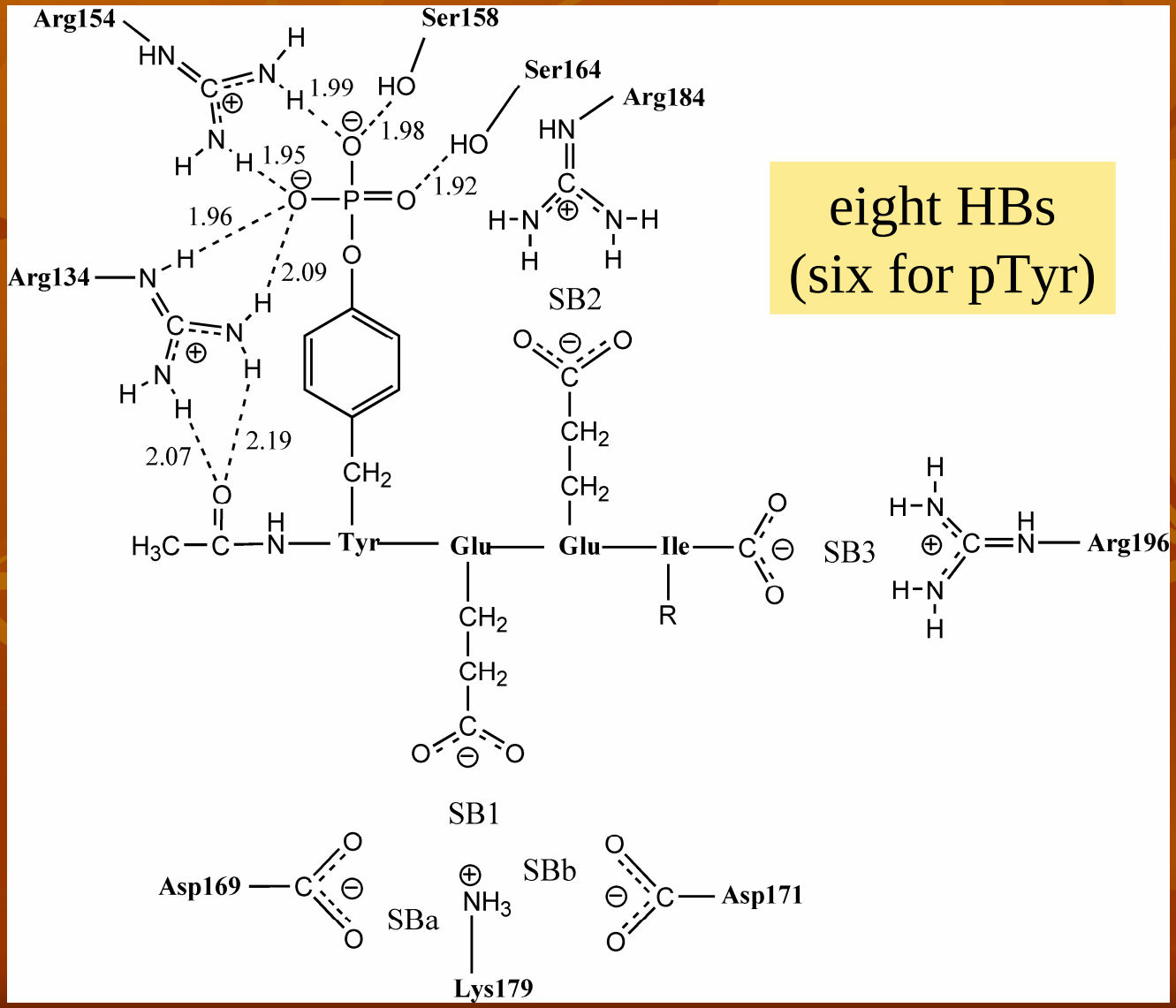
Ref. Tong et al. *J. Mol. Biol.* 256 (1996) 601-610

Role of the SH2 domain in ST Biology



Source: Pawson, *Cell* (2004)

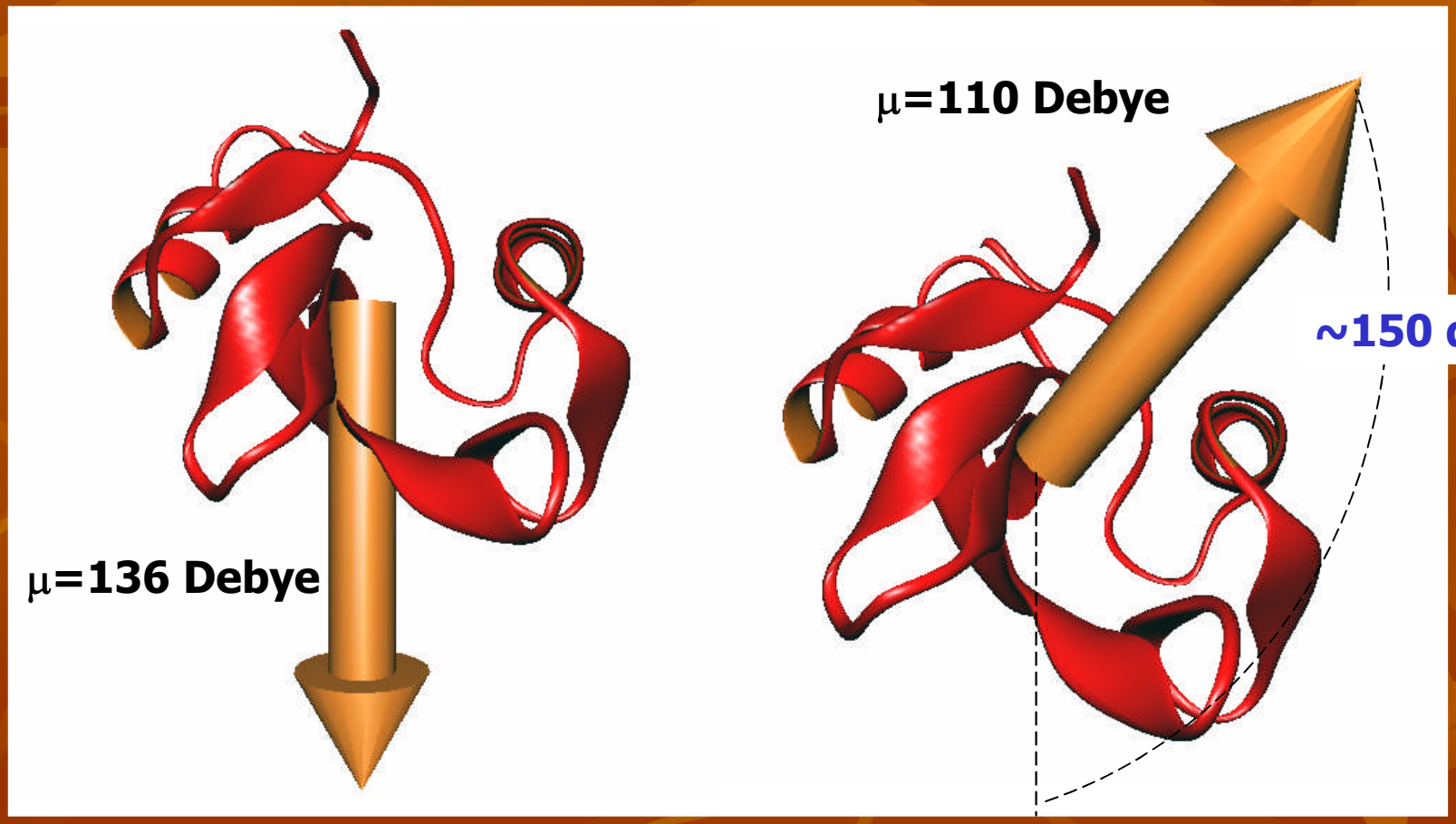
pYEEI-SH2 interactions



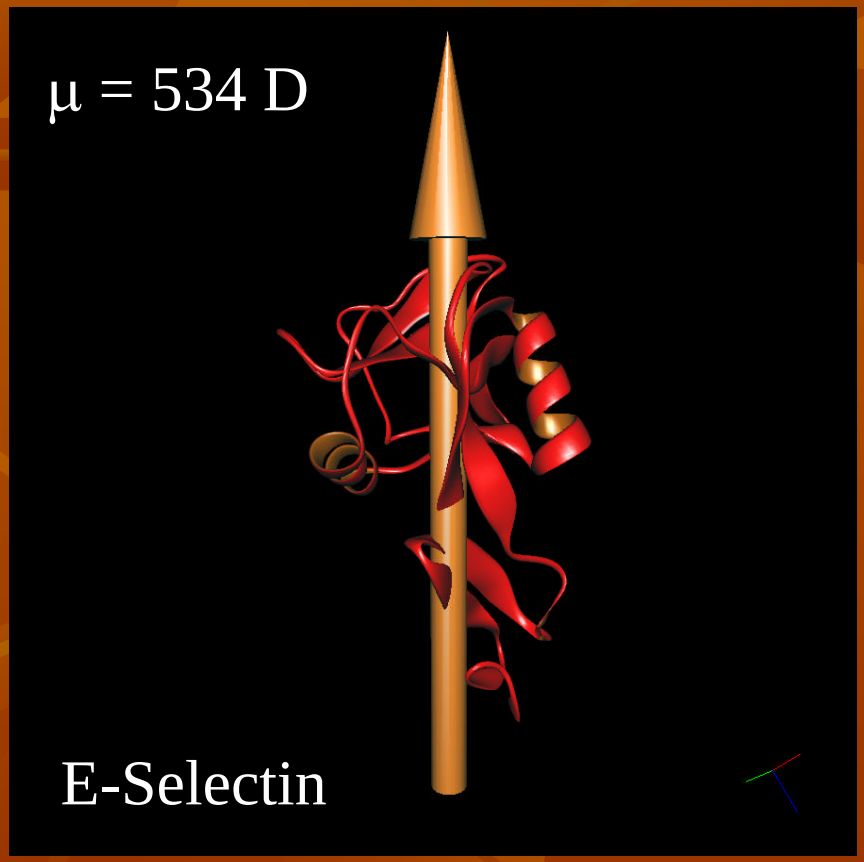
eight HBs
(six for pTyr)

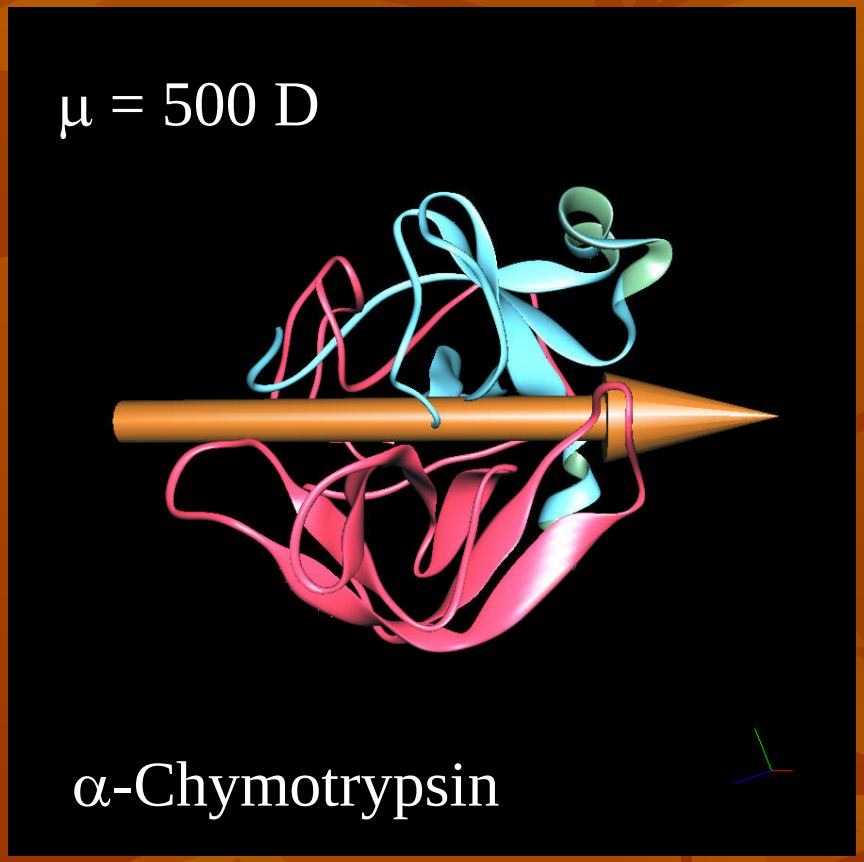
Discovery of Quantum Effects in ST Biology

[Pichierri, *Biophys.Chem.* 109 (2004) 295-304]



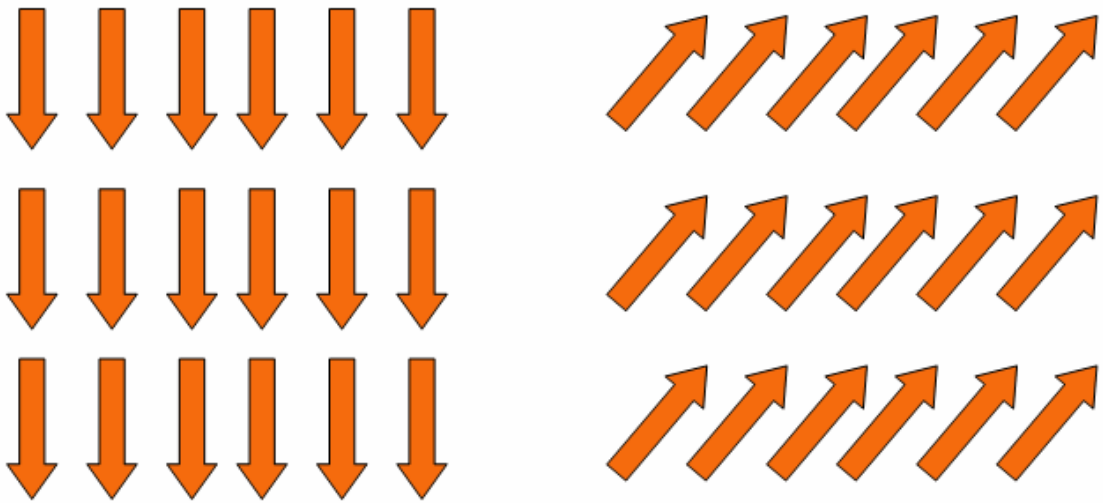
Protein Macrodipoles





Bio-Nanoelectronics: array of macrodipoles

***n* SH2 + *n* Peptide ⟶ *n* (SH2:Peptide)**

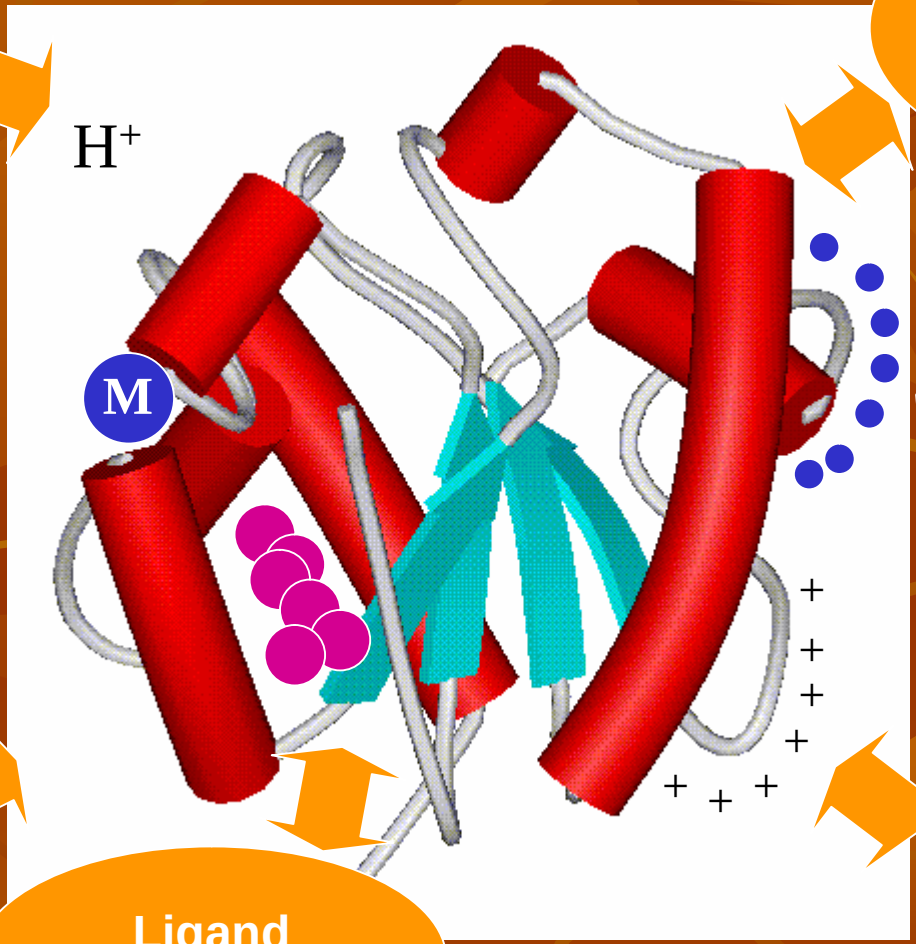


ON **OFF**

Protein-based devices

Protonation & de-protonation

Conformational change



Electron transfer

Solvation

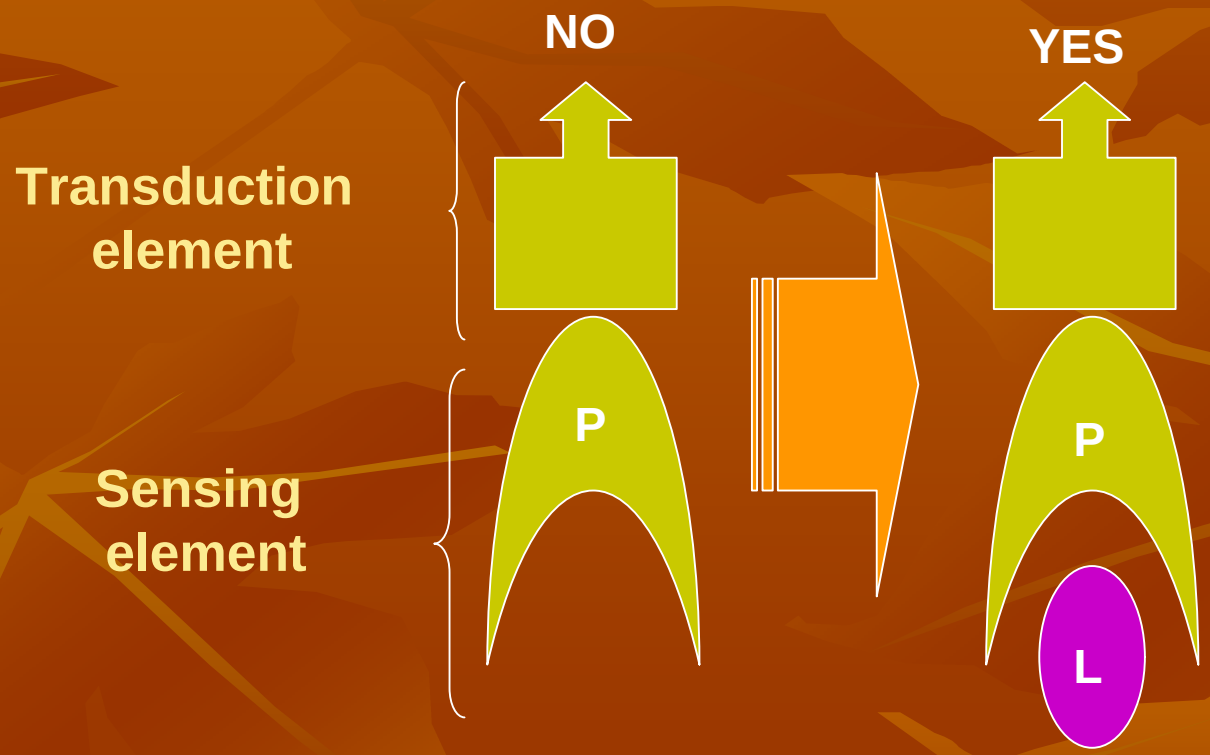
Molecular recognition

Ligand binding

Polarization

Biosensor

Detection (Macro-scale)

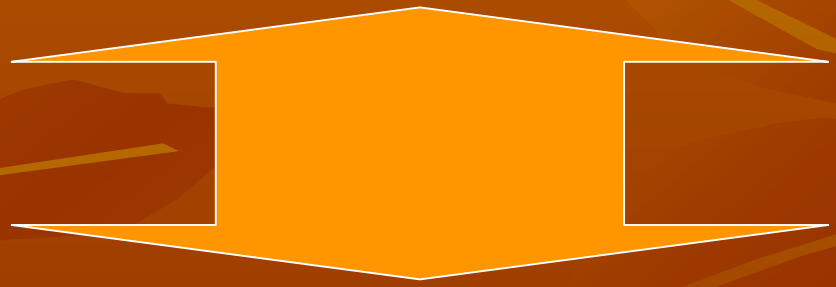


Molecular recognition & binding (Nano-scale)

Learning from Nature:

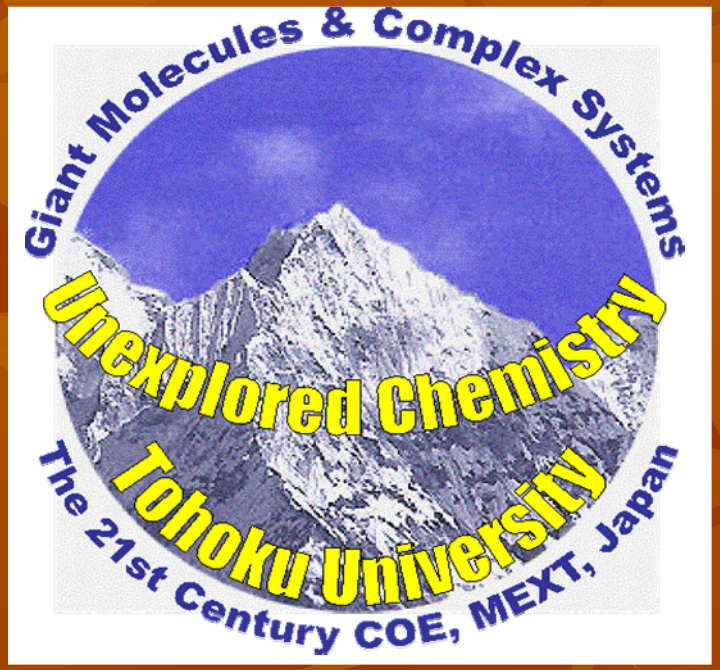
Biomimetics

Bios(=life) + Mimesis(=imitation)



Nanotechnology

Financial support:



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