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New Materials for Emerging Desalination Technologies

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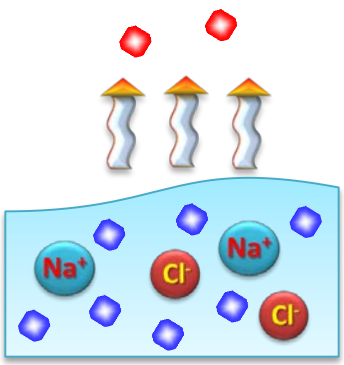
Outline

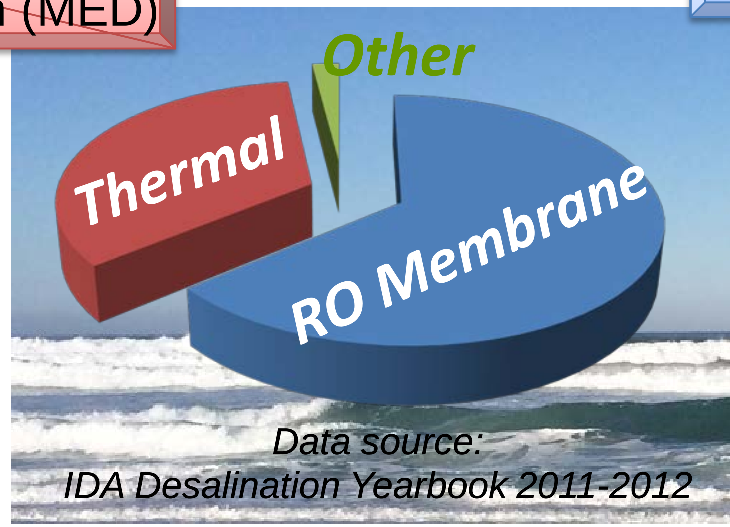
- State-of-the-art and emerging desalination technologies
  - Reverse osmosis (RO) membrane and thermal processes
  - Solar thermal, membrane distillation, forward osmosis
- Motivation for developing new materials
  - Alternative, sustainable energy sources
  - Membranes with better separation capability
  - Antifouling membranes

State-of-the-art Seawater Desalination

Thermal Processes

Multi-stage flash (MSF)
Multi-effect distillation (MED)

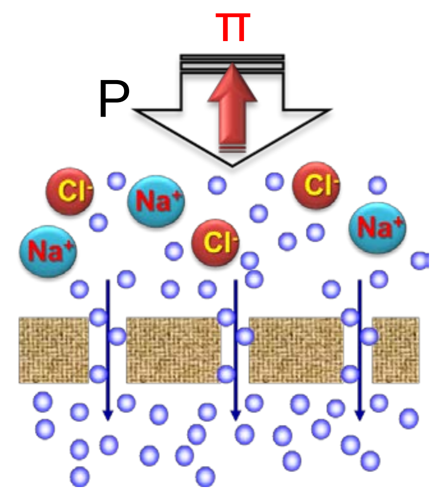




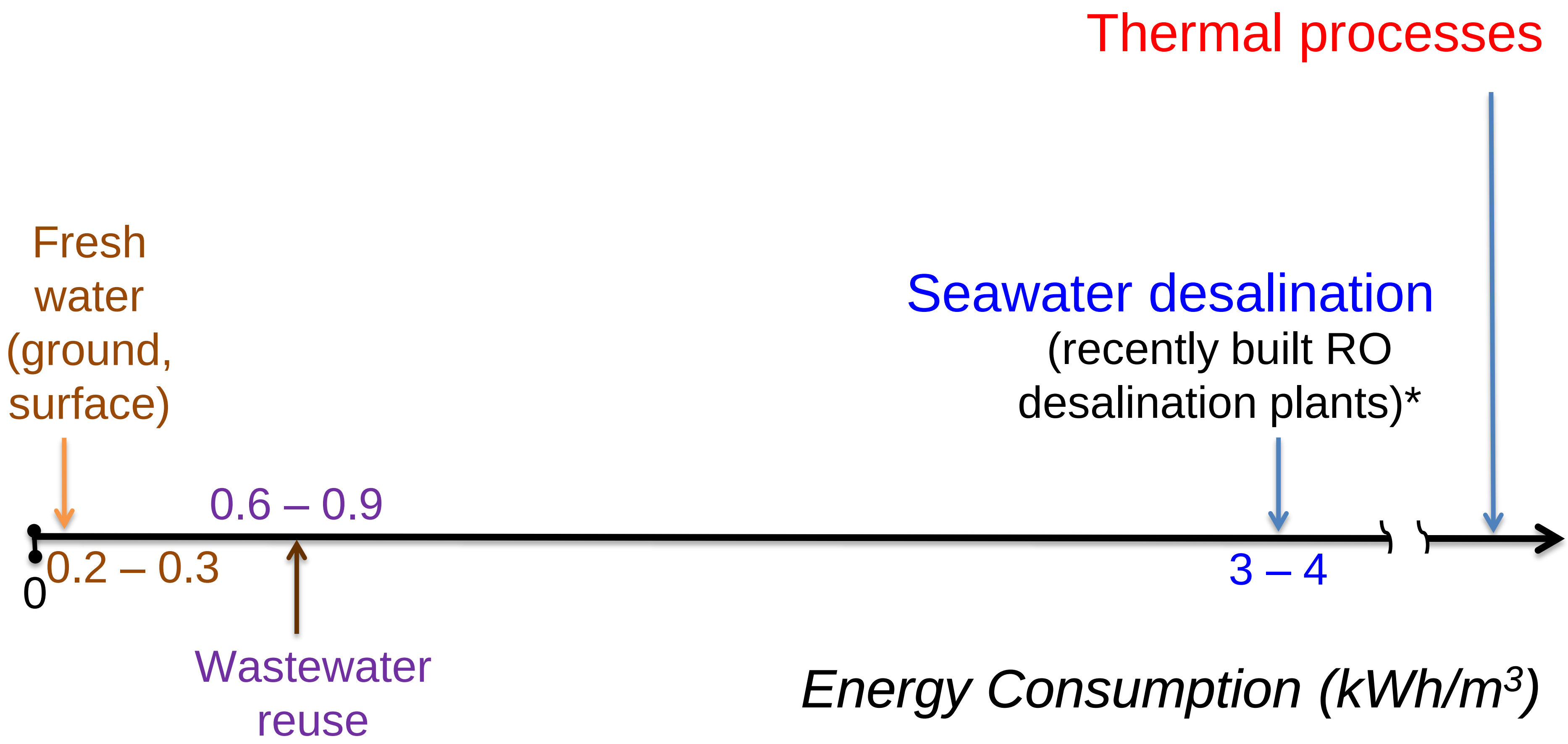
Data source:
IDA Desalination Yearbook 2011-2012

Physical Separation

Reverse osmosis (RO)



Energy Consumption of Desalination



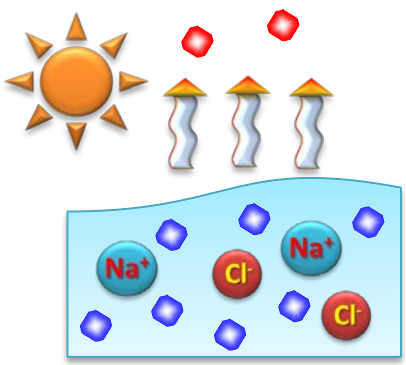
Elimelech and Philip, *Science*, 2011, 333

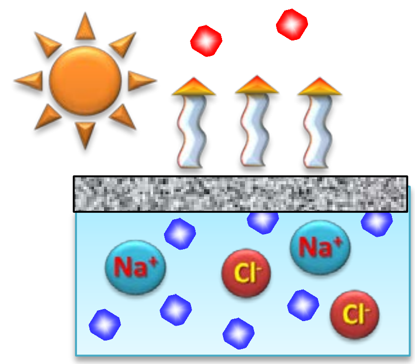
Emerging Desalination Technologies

Thermal Processes – use sustainable energy

Goal: use solar or low-temperature waste heat as the source of energy.

Graphene-based



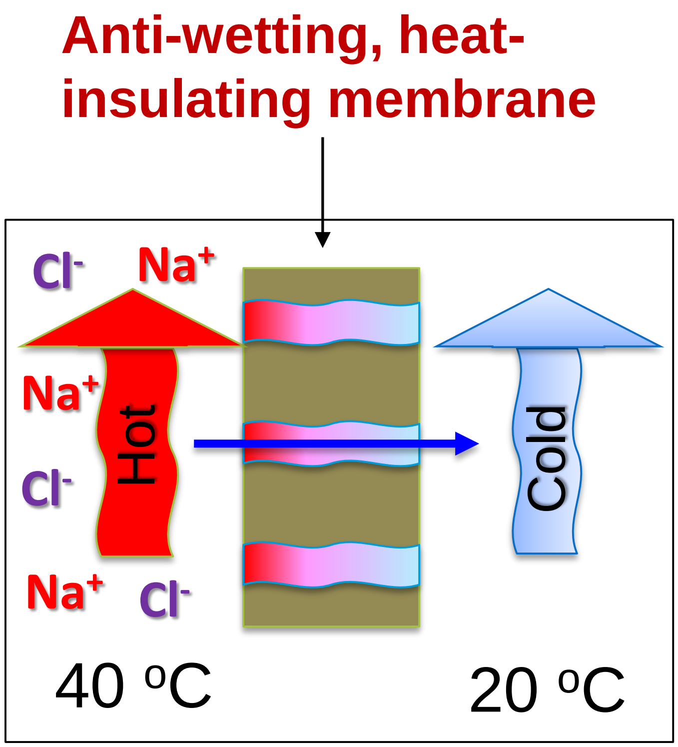


Solar desalination by heat localization

Emerging Desalination Technologies

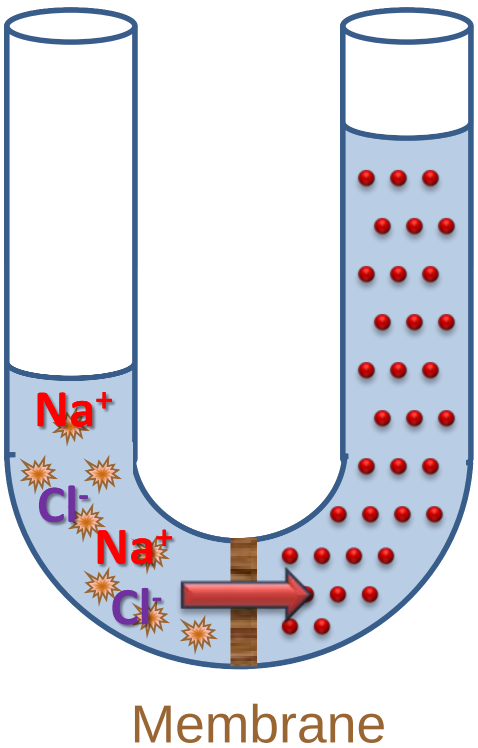
Membrane Distillation

Goal: use solar or low-temperature waste heat as the source of energy.



Emerging Desalination Technologies

Forward Osmosis (FO)

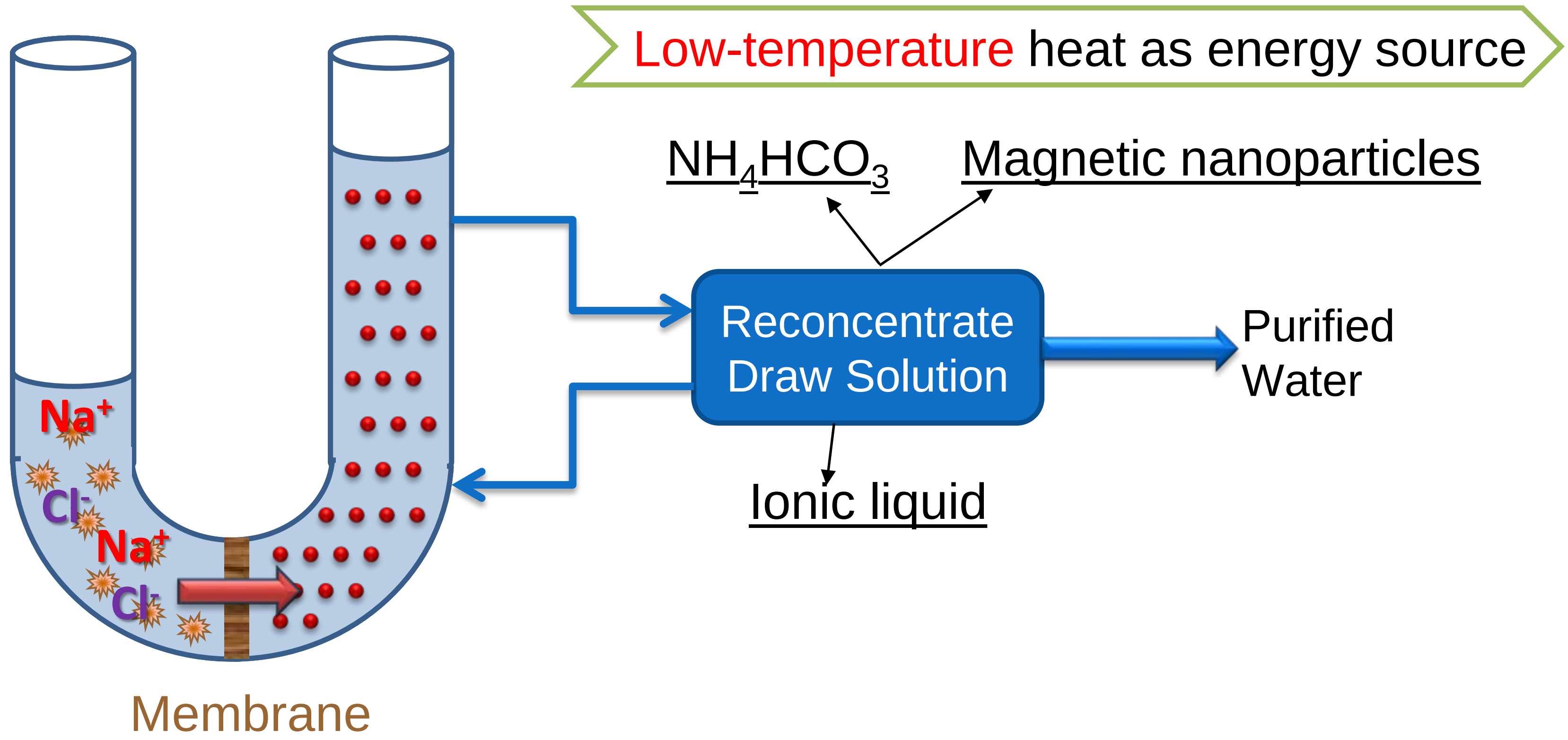


Real expert in FO: Shark

Better fouling resistance:
Unique applications to treat most challenging waters

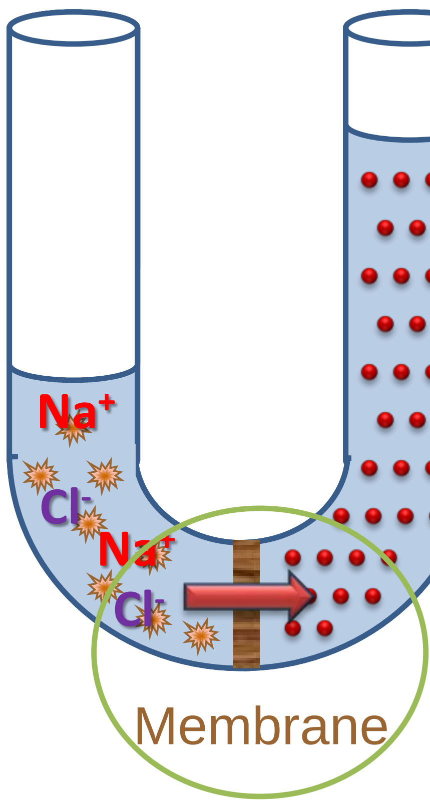
Emerging Desalination Technologies

Forward Osmosis (FO)

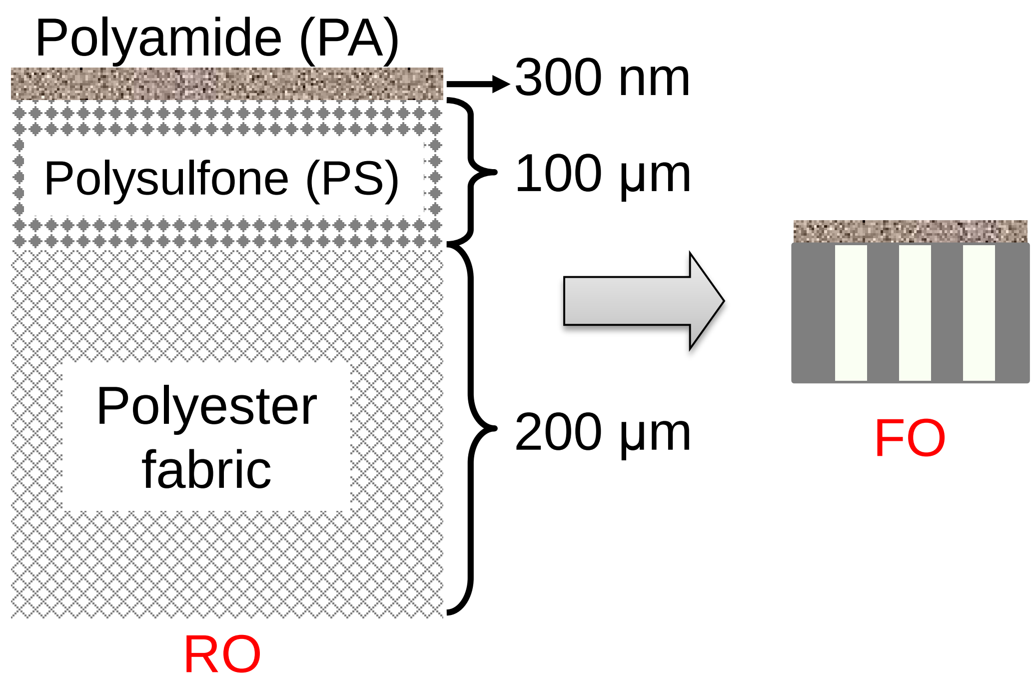


Emerging Desalination Technologies

Forward Osmosis (FO)

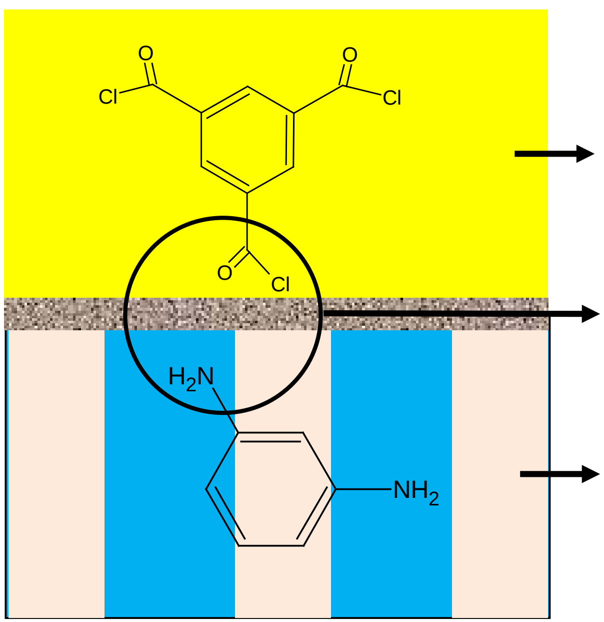


Thin, hydrophilic, open membrane support



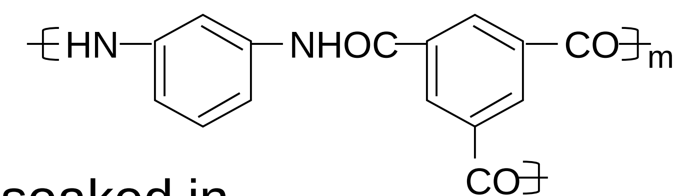
Traditional Desalination Membrane Materials

- Polyamide thin film composite (TFC)
  - Membrane fouling
  - Poor chlorine tolerance
  - Poor removal of neutral species



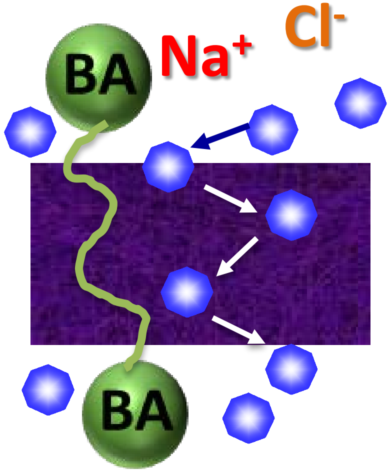
Organic solution of TMC

Polyamide thin film

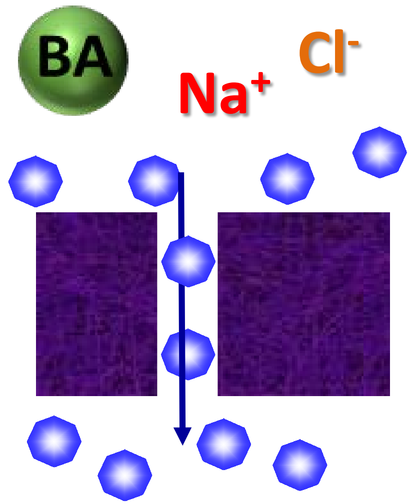


Polysulfone soaked in aqueous solution of MPD

Design Better Desalination Membrane

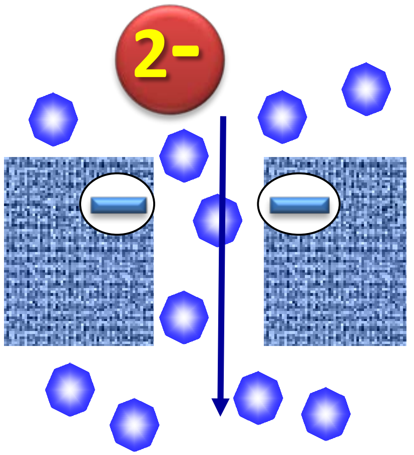


Partition-diffusion



Size exclusion

(0.3 - 0.7 nm)



Charge effect

Emerging Membrane Materials

Aquaporin

Carbon Nanotube

Artificial Channel

Superfast water transport

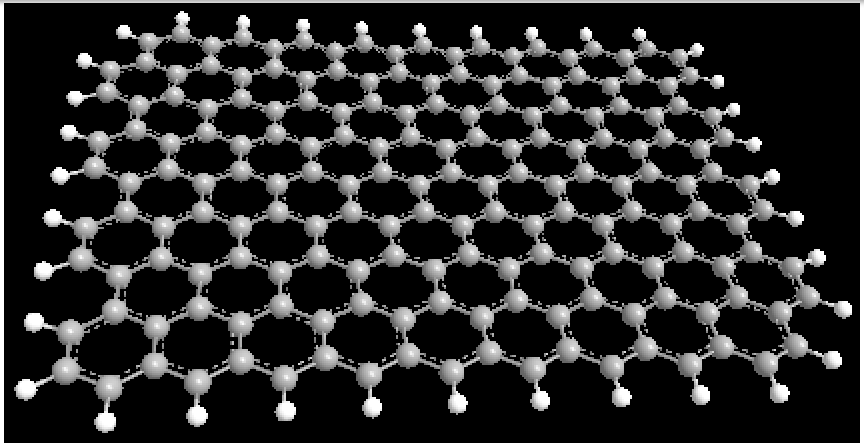
- 10^4 – 10^5 faster than theoretical prediction due to
  - Extreme smooth walls
  - Water-hating surface
  - Molecular alignment

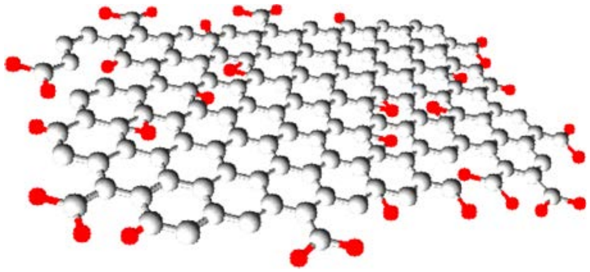
Gated channel for selectivity

- Size exclusion governing selectivity
- Charged functional groups to gate the channel for enhanced selectivity

Emerging 2D Membrane Materials

Graphene & Graphene oxide





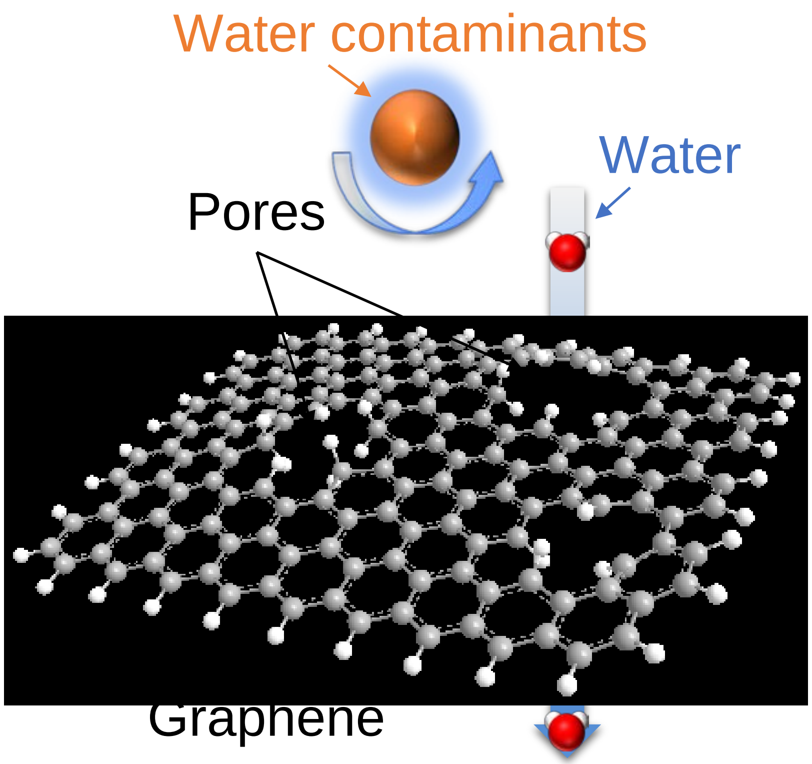
MoS_2

Mxene (e.g., $Ti_3C_2O_x$)

Single-layer Nanoporous Membrane

Superfast water transport

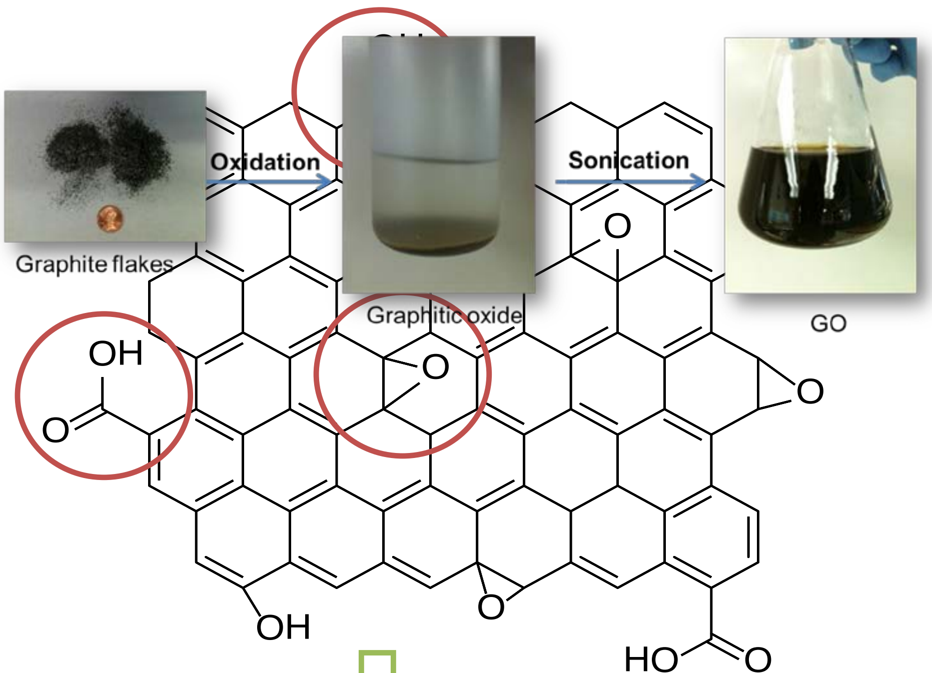
Pore size for selectivity

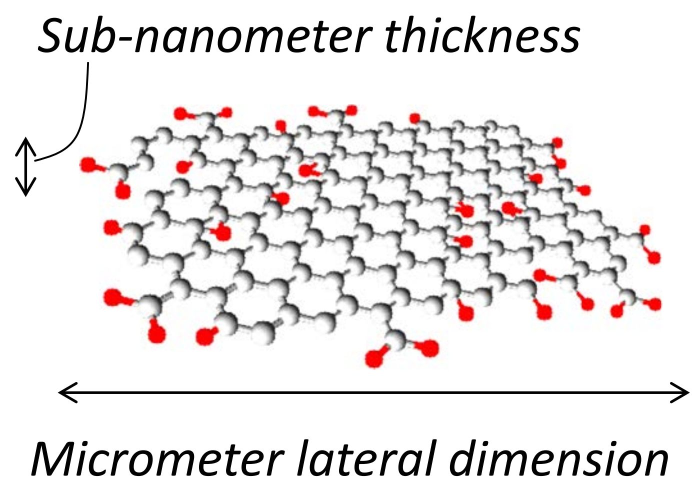


Intriguing Properties of Graphene Oxide (GO)

Hydroxyl (-OH), carboxyl (-COOH), and epoxide (-O-) groups

Thin 2D material made of single-layer carbon lattice

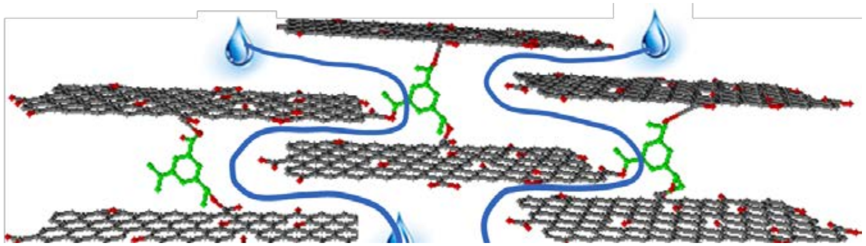




Low cost, facile synthesis, flexible functionalization

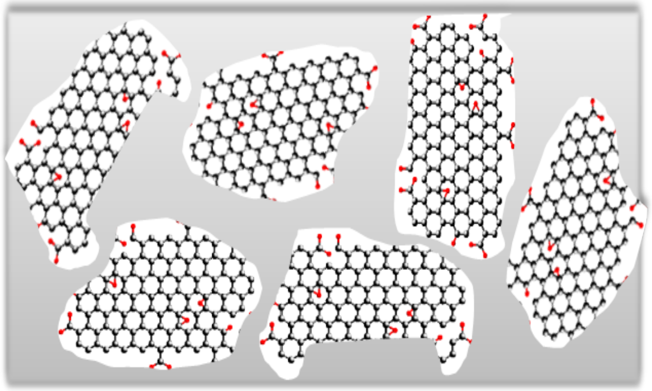
Stackable – convenient for thin-film synthesis

Layer-stacked GO Membranes

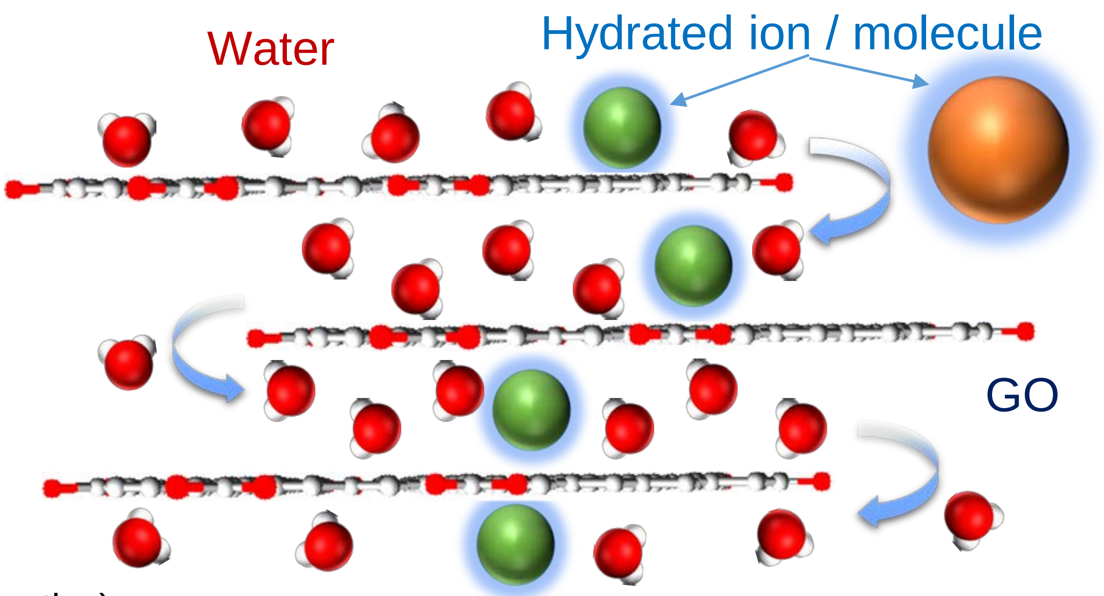


Multiple layers of stacked, bonded GO nanosheets as molecular / ionic sieves

Top view



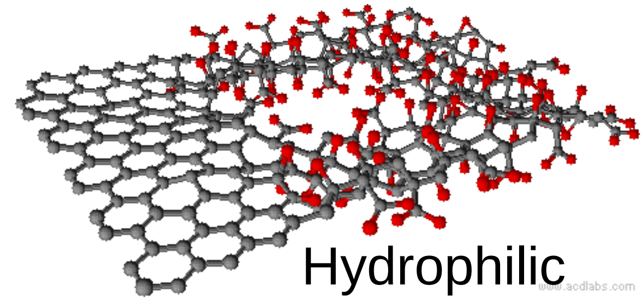
Cross section



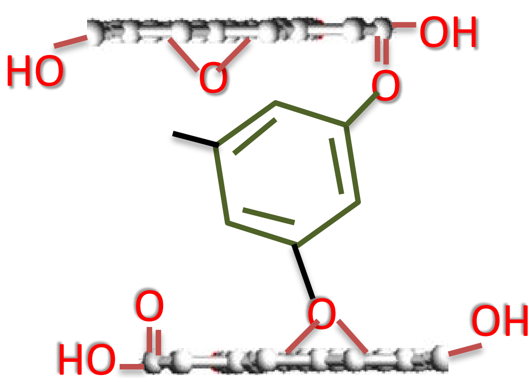
Mi, *Science*, 2014, 343 (Perspective)

GO Membrane Synthesis

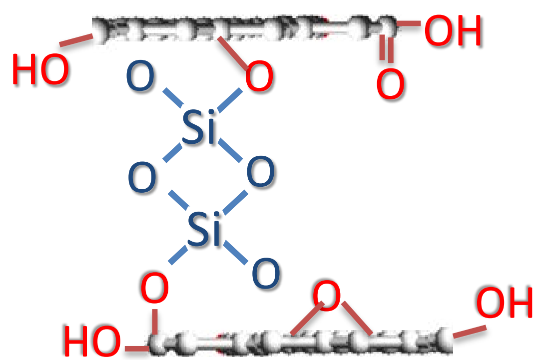
- Proper bonding to prevent the disintegration of GO membrane in aqueous environment.



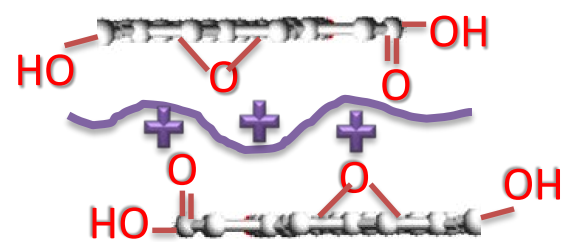
GO-TMC



GO-silica



GO-PAH



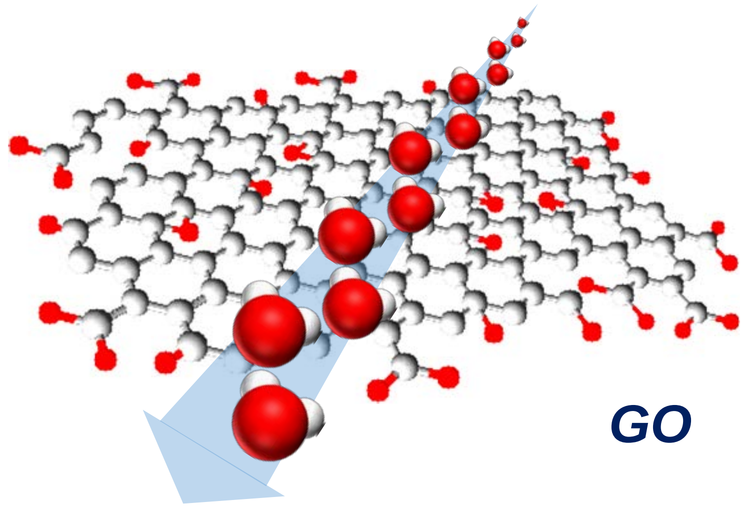
Hu and Mi, *Environ. Science & Technology*, 2013, 47, 3715

Zheng and Mi, *Environ. Sci: Water Res & Techno.*, 2016, 2, 717

Hu and Mi, *Journal of Membrane Science*, 2014, 469, 80

Water Permeability of GO Membrane

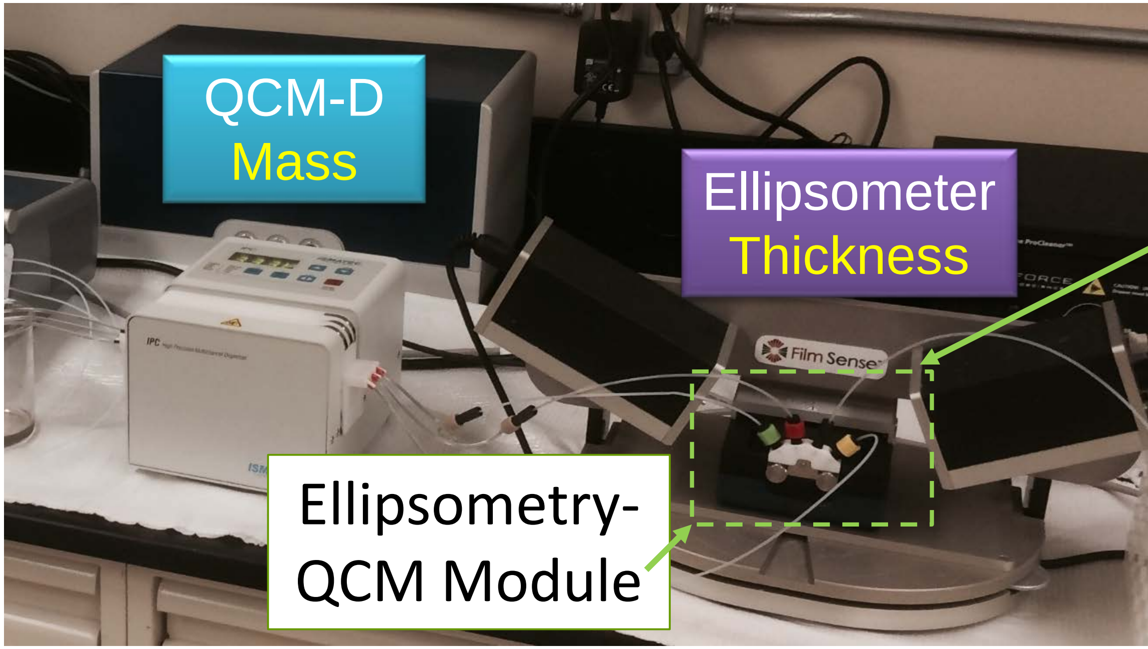
Superfast water transport in graphene-walled channels

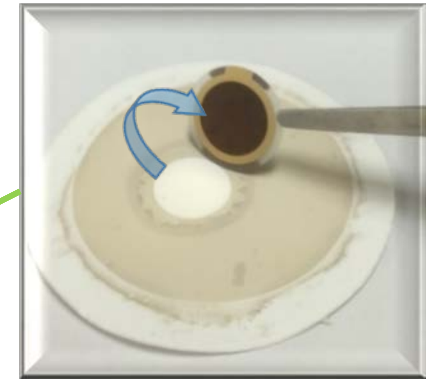


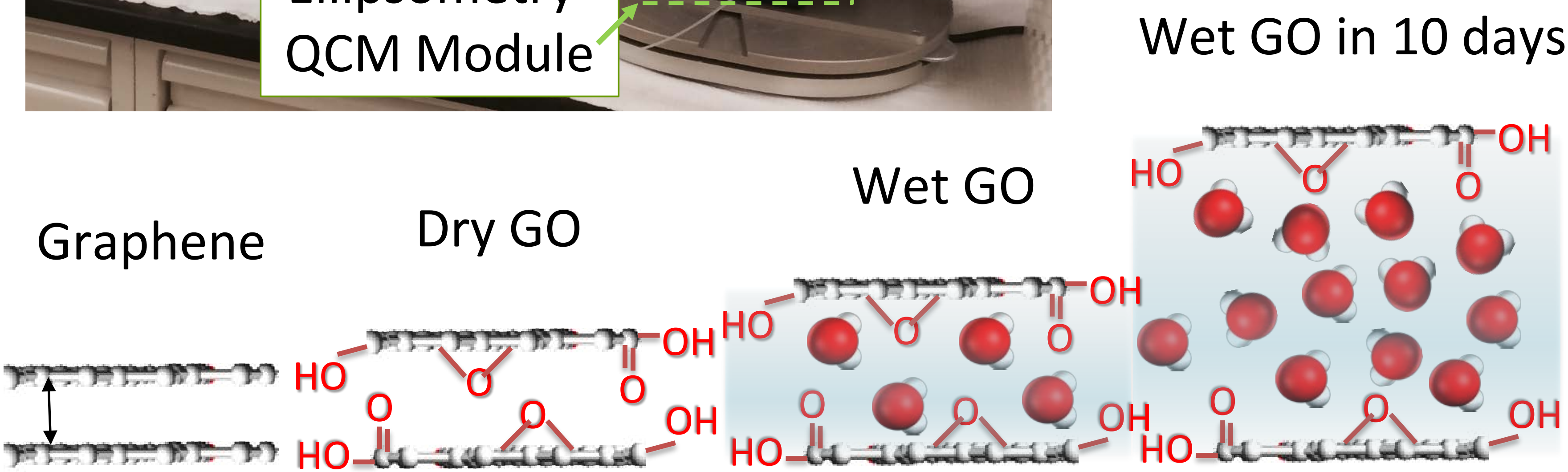
High water permeability
(3-4 orders of magnitude enhancement in water flux)

- Smooth wall
- Hydrophobic surface
- Square ice structure

GO Membrane Swelling in Water

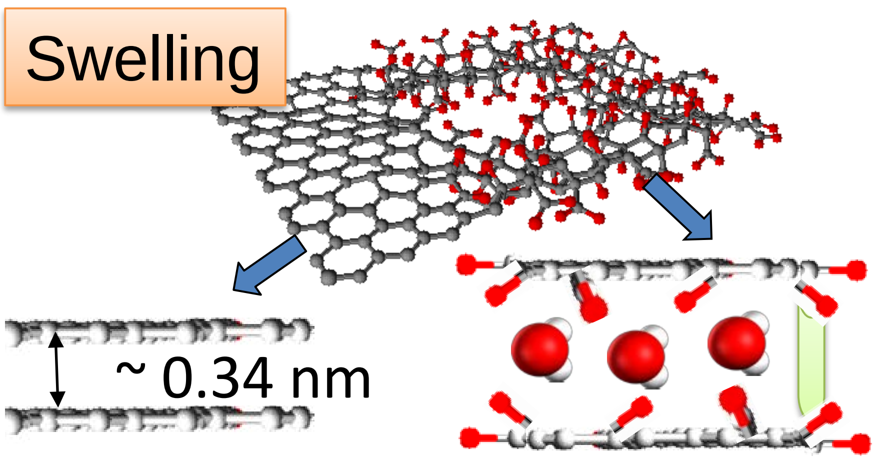


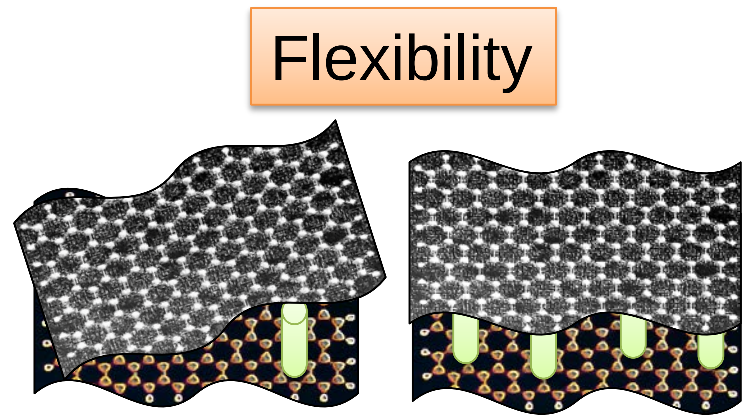




Selectivity of GO Membranes

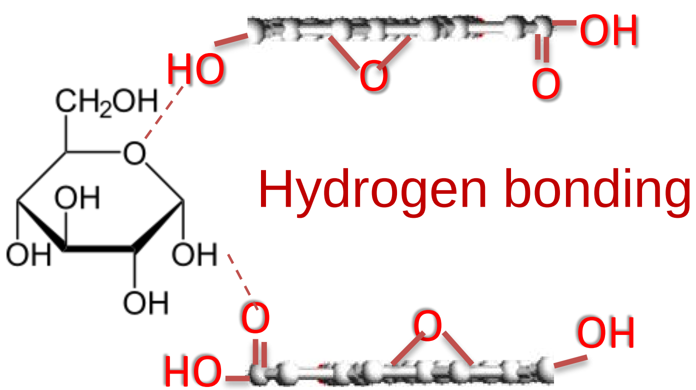
- Precise spacing control to achieve desired selectivity

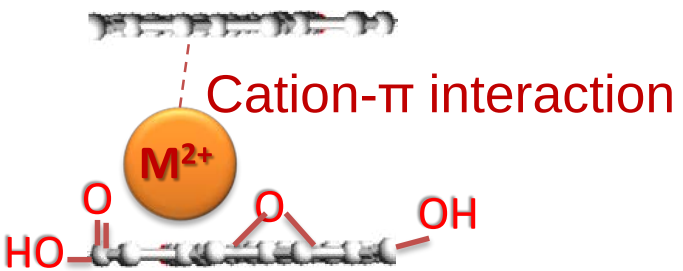




Enhanced Selectivity of Stacked Membrane

- Reduced partitioning/diffusion to enhance selectivity for
  - Organic molecules
  - Heavy metals





Summary

- Are we ready for desalination?
- New materials are pushing forward more sustainable desalination technologies
- Unique potential of 2D membrane materials
  - 2D shape of GO nanosheets allows facile approach to synthesize novel membranes with excellent stability
  - Tunable functionality offers selective removal of contaminants.
  - Understanding the swelling phenomena is the key to better control interlayer spacing and enhance membrane selectivity

Acknowledgements

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- Department of Energy, US-China Clean Energy Research Center for Water and Energy Technologies (CERC-WET).