Lecture Note #1 (Fall, 2022)

Introduction to surface & interface

1. Introduction to lecture (syllabus)
2. Introduction to surface, why surface science?

Reading: Kolasinski, Introduction

2022 Fall
458-622 Advanced Surface Chemistry, 표면화학특론

LECTURER: Professor Yung-Eun Sung (성영은)
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OUTLINE

This class deals with basic principles of surface and interface at solid and liquid. Those include structures and adsorbates, experimental techniques, thermodynamics & kinetics on surface, liquid interfaces, and application to catalysis and nanoscience.

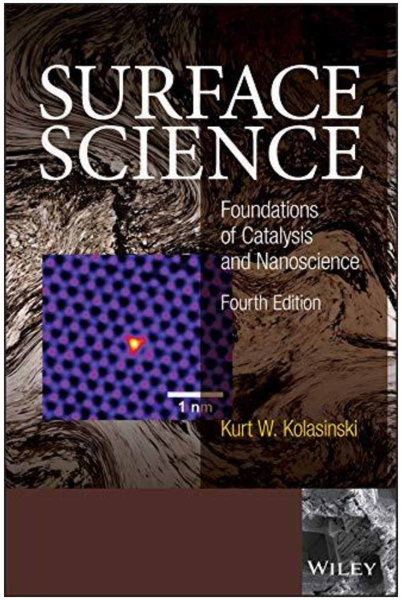
KEYWORD

Surface, Interface, Geometric surface structure, Electronic structure, Adsorption, Desorption, Surface thermodynamics, Surface kinetics, Surface tension, Surfactant, Catalysis, Electrocatalysis, Nanoscience and so on

TEXTBOOK

Kurt W. Kolasinski, *Surface Science – Foundations of Catalysis and Nanoscience* (4th edition), Wiley. 2020. (3rd ed. Also available)

(e-book(3rd ed) available in SNU Library)



REFERENCES

G. A. Somorjai, Introduction to Surface Chemistry and Catalysis, John Wiley. (e-Book available in SNU Library)

Duncan J. Shaw, Introduction to Colloid and Surface Chemistry, John Wiley.

(Korean reference: 임재석, 임굉, 콜로이드과학 및 표면화학, 내하출판사, 2015)

R.M. Pashley, Applied Colloid and Surface Chemistry, 2nd ed., Wiley, 2021.

R.J.D. Tilley, Crystals and Crystal Structures, 2nd ed., Wiley, 2020.

R.J.D. Tilley, Understanding Solids – The Science of Materials, 3rd ed., Wiley, 2021.

and further specific references will be recommended

SCHEDULE (may be modified)

1. Introduction to Surface & Interface (Introduction) (1 week)
2. Surface and Adsorbate Structure (ch.1) (1-3 weeks)
3. Experimental Probes and Techniques (ch.2) (4-5 weeks)
4. Chemisorption, Physisorption and Dynamics (ch.3) (6-7 weeks)
5. Thermodynamics and Kinetics of Adsorption and Desorption (ch.4) (8-9 weeks)
6. Thermodynamics of Surface and Interface (ch.5) (10-11 weeks)
7. Liquid Interfaces (ch.5) (12-13 weeks)
8. Application to Catalysis and Nanoscience (ch.6, 7, 8) (14-15 week)

GRADING (≥B$^+$ <80% or Department guide) Midterm Exam 40%,
Final Exam 40%, Homeworks & Attendance 20 %

LECTURE ROOM & TIME: Rm #302-409, 9:30-10:45 Mon. & Wed.

OFFICE HOUR: Rm #302-721, 11:00-12:00 & afternoon on Mon. & Wed.

TA: ChaeYeon Yang(양채연), e-mail: cyyang@kist.re.kr, didcodus46@snu.ac.kr,
phone: 010-9379-8385

*Lectures on National Holidays are held in classroom or online using zoom. Also zoom video file will be provided.

September 12(Mon), Chuseok
October 3(Mon), National Foundation Day
October 10(Mon), Hangul (Proclamation) Day

*Lectures will be provided by online zoom and/or zoom video file for official business trips

November 2(Wed), the Korean Electrochemical Society

Nov. 7, 9(Mon, Wed), Vietnam

Dec. 12, 14(Mon, Wed(Final Exam)), Singapore

(Oct. 12(Wed), Atlanta, not yet decided)

*No make-up: all lectures & exams will be in scheduled class hours

*Extra zoom video file(s) may be provided if needed

Core coursework in CBE Graduate:
"Advanced Surface Chemistry"

Previous Lecture Evaluations(강의평가 결과)

Depth: **Specific(deep) vs. Non-specific(broad)**

Difficulty: **Difficult vs. Easy**

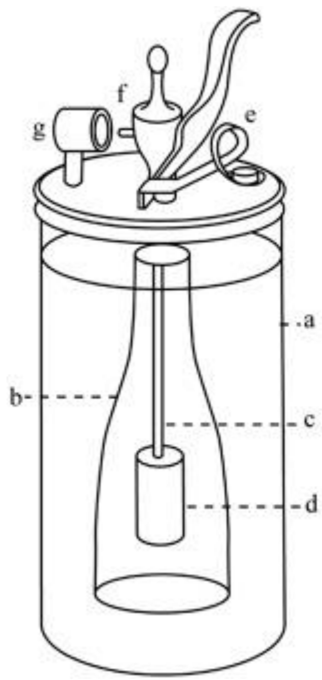
Contents: **Too much vs. Not enough**

How to do?
What should do?

History of surface science

Early 1800s

- Spontaneous spreading of oil on water: Benjamin Franklin
- Platinum-surface-catalyzed reaction of H_2 & O_2 in 1823 (Dobereiner): portable flame (“lighter”)
- Discovery of heterogeneous catalysis by 1835: Kirchhoff, Davy, Henry, Philips, Faraday, Berzelius
- Photography by 1835: Daguerre process
- Study of tribology or friction

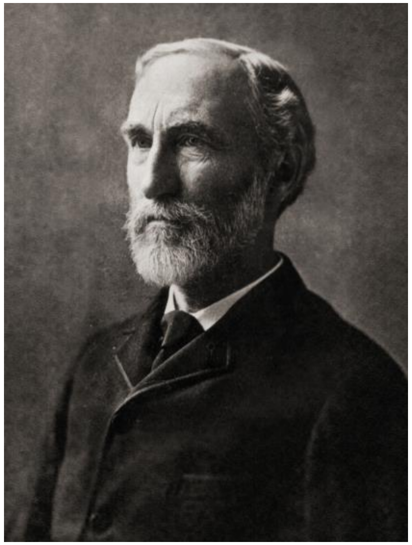


The Döbereiner lighter set-up

a : cylinder
b : open bottle
c : wire
d : piece of zinc
e : tap
f : nozzle
g : support for platinum

1860-1912

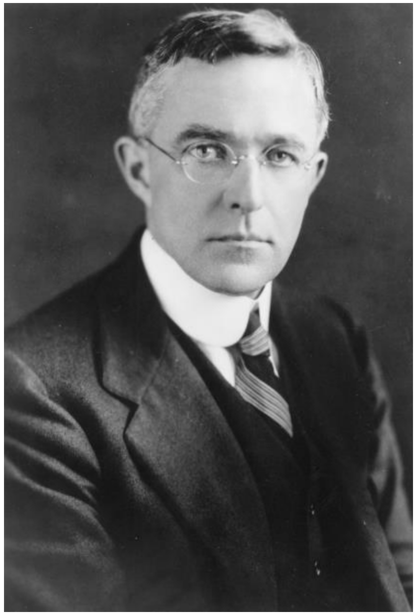
- Surface-catalyzed chemistry-based technologies: Deacon process ($2HCl + O_2 \rightarrow H_2O + Cl_2$), SO_2 oxidation to SO_3 (Messel, 1875), CH_4 reaction with steam to CO & H_2 (Mond, 1888), NH_3 oxidation (Ostwald, 1901), C_2H_4 hydrogenation (Sabatier, 1902), NH_3 synthesis (Haber, Mittasch, 1905-12)
- Surface tension measurement → thermodynamics of surface phases (Gibbs, 1877)



- Colloids (Graham, 1861), micelles (Nageli), metal colloids (Faraday) → paint industry, artificial rubber in early 20th century

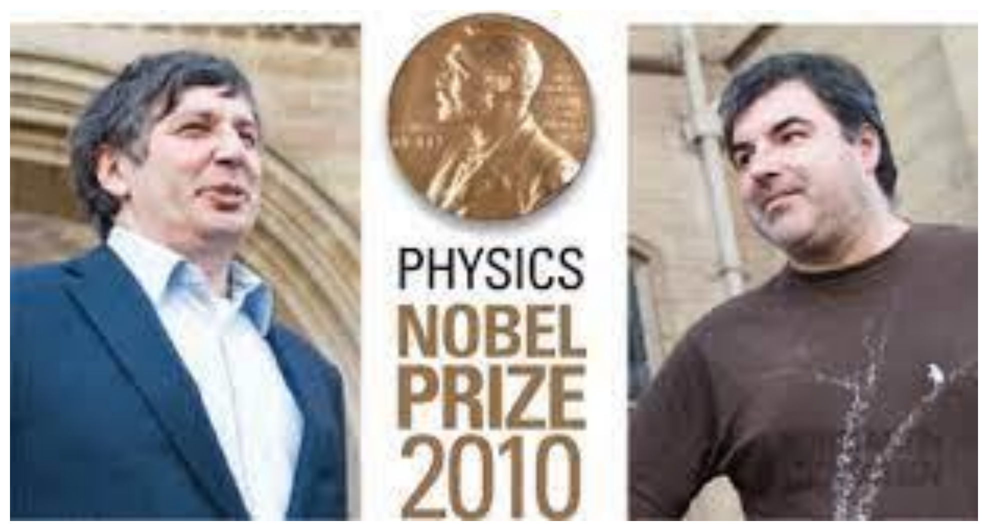
Early 20th century

- Light bulb filament, high-surface-area gas absorbers in the gas mask, gas-separation technologies → atomic & molecular adsorption (Langmuir, 1915)
- Studies of electrode surface in electrochemistry (from 19th century)
- Surface diffraction of electrons (Davisson & Germer, 1927)
- Surface studies: Germany (Haber, Polanyi, Farkas, Bonhoefer), UK (Rideal, Roberts, Bowden), USA (Langmuir, Emmett, Harkins, Taylor, Ipatief, Adams), and other countries



After 1950s & 2000s

- Gas-phase molecular process on the molecular level
- Ultra high vacuum (UHV) system
- Surface characterization techniques
- Scanning tunneling microscope(STM, Binning & Rohrer,1983) (Nobel Prize in 1986): atomic scale image & manipulation
- Graphene (Novoselov & Geim, 2004) (Nobel Prize in 2010)
- Nobel Prize in 2007 to Gerhard Ertl for “chemical processes on solid surfaces”
- Nanotechnology in 2000’s



Why surface science?

Surfaces and interfaces

- Surface: interface between immiscible bodies
- Outer space: solid-vacuum interface
- Surfaces on earth are exposed to another solid or gas or liquid → interface: *s/s, s/l, s/g, l/l. l/g*

Chemical engineering, chemistry, physics, inorganic, semiconductor, nanotechnology, energy, electrochemistry, materials, organic, polymer, biological applications

Polymer surfaces

- Surface is very different from bulk due to structural unit connected covalent chemical bonds

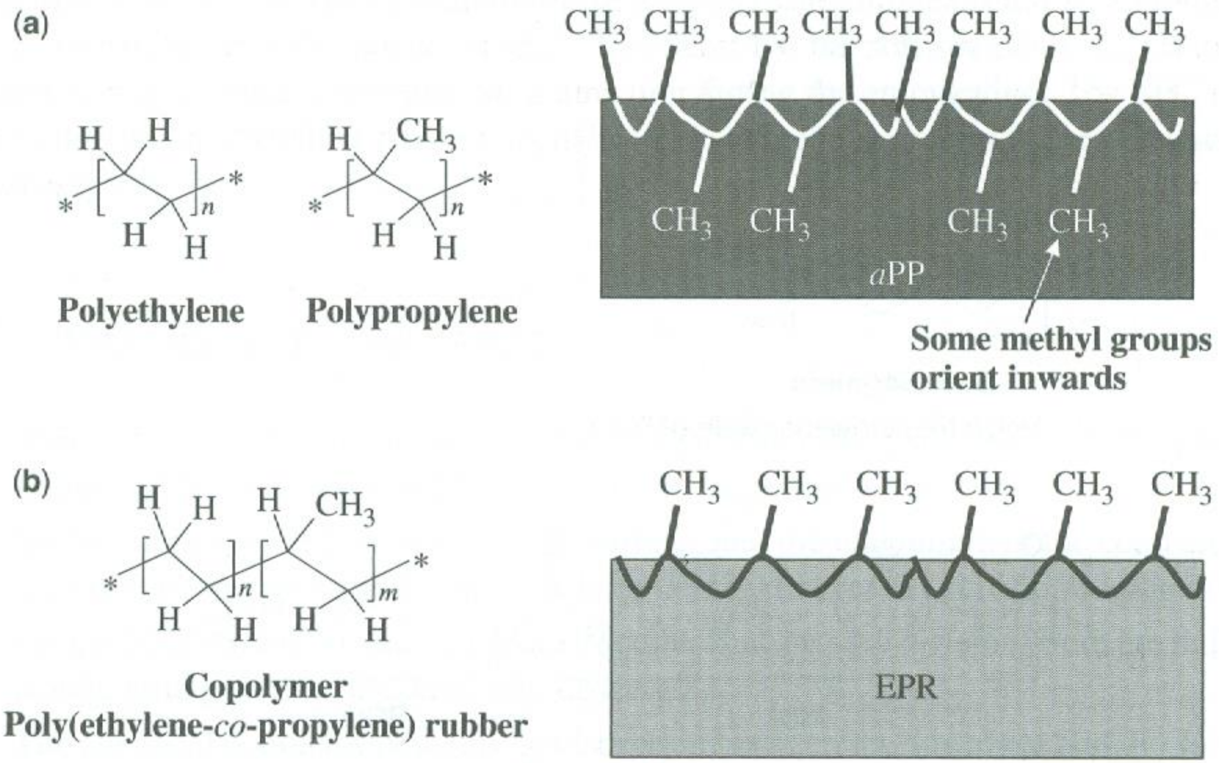
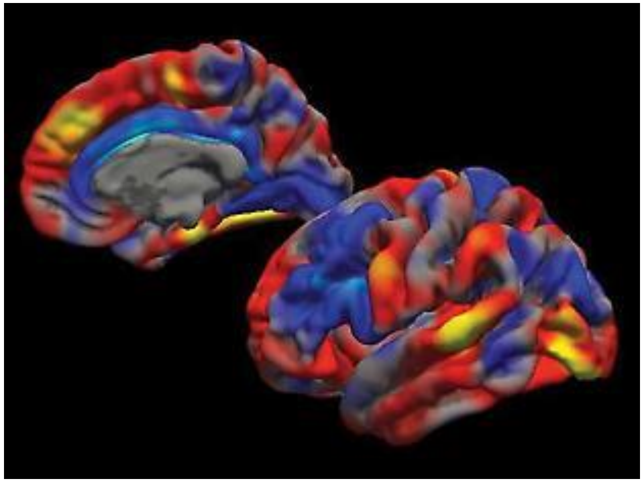


Figure 2.38. (a) Structure of polyethylene, polypropylene, and their copolymer, poly(ethylene-*co*-propylene) rubber (EPR). (b) Schematic for the orientation of surface CH_3 groups on the atactic polypropylene (*a*PP) and the EPR.

Somorjai, *Introduction to Surface Chemistry and Catalysis*

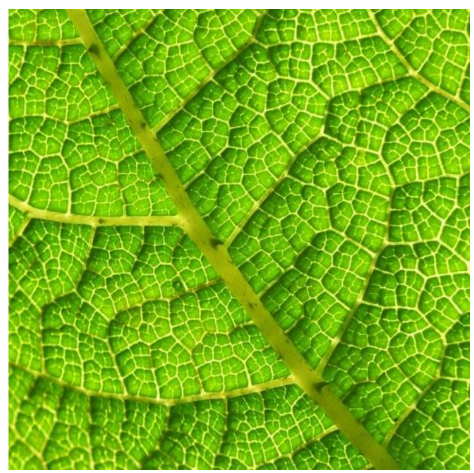
Biological surfaces

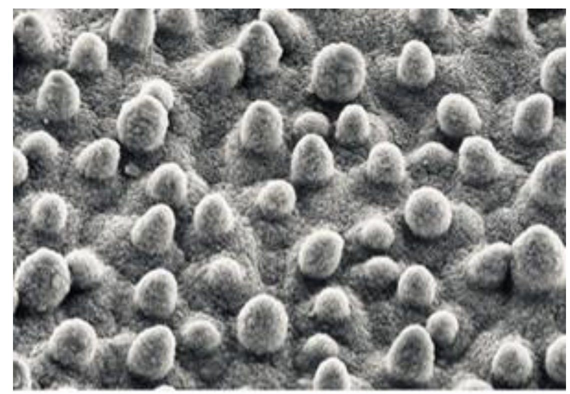
Brain

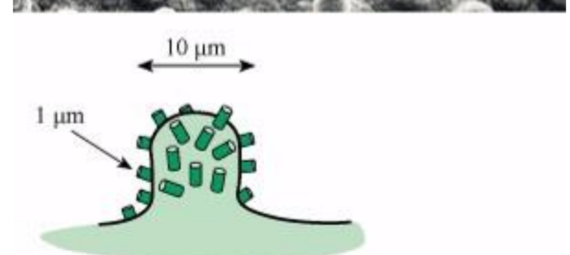


australasianscience.com.au

Leaf

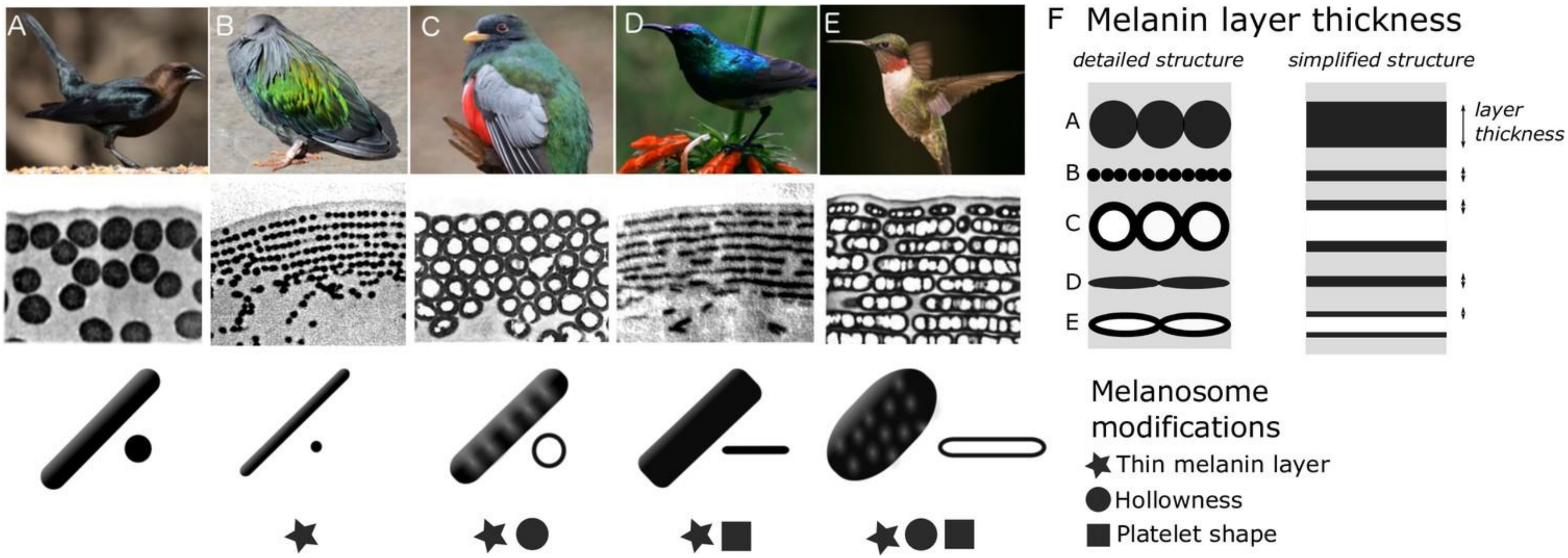






Biological surfaces

Bird feathers



Sea urchin(성게)

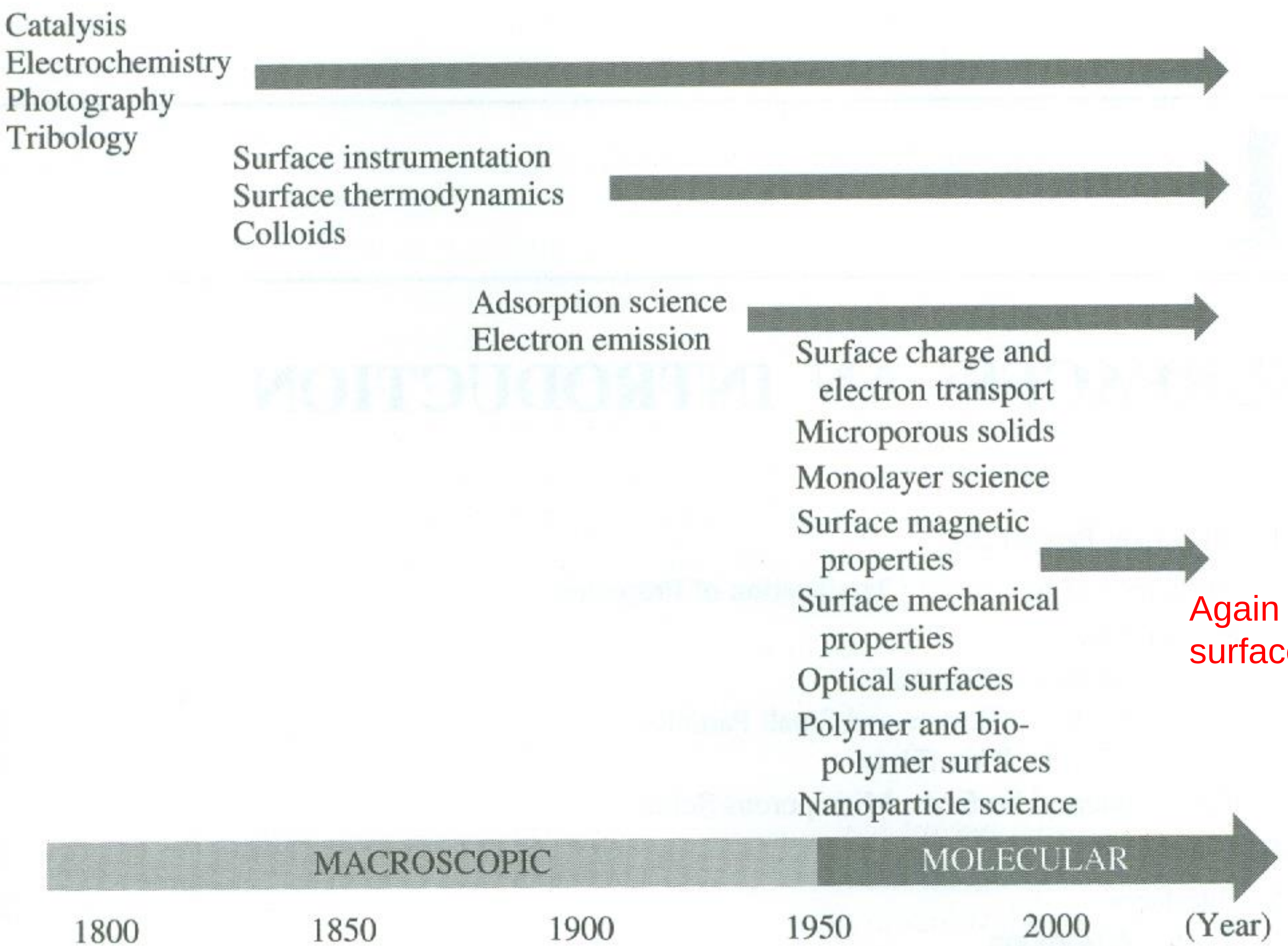


Figure 1.1. Timeline of the historical development of surface chemistry.

Again
surface science!

Somorjai, *Introduction to Surface Chemistry and Catalysis*

The techniques of surface science

- AES, AFM, EELS, XPS(ESCA), EXAFS, FEM, FIM, FTIR, HEIS, APXPS, HREELS, IRAS, ISS, LEED, LEIS, NEXAFS, NMR, RBS, SEM, SERS, SFG, SHG, SIMS, STM, TEM, TDS, UPS, XANES, SPS, XRD… (see Table 1.1)

- Surface properties: structure, composition, oxidation states, chemical properties, electronic properties, mechanical properties → atomic resolution, smaller energy resolution, shorter time scales, *in situ*, high pressure

- Sources: electron, atoms, ions, photons(X-ray, UV, visible, IR…)

electron	photons
TEM	XRD
SEM	XPS
TED	UPS
EELS	EXAFS
AES	XANES
LEED	IR

Interfaces

- On earth, surfaces are always covered with a layer of atoms or molecules → interfaces

s/g, s/l, l/l, s/s/ l/g

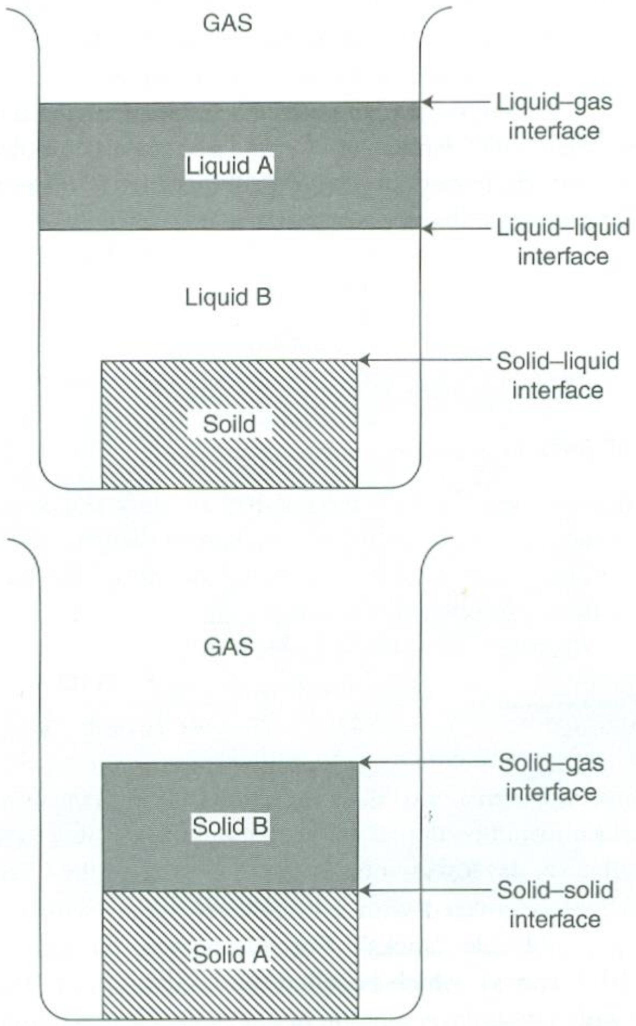


Figure 1.12. Schematic diagram of interfaces (e.g., solid–liquid, liquid–liquid, liquid–gas, solid–solid, and solid–gas interfaces).

Somorjai, *Introduction to Surface Chemistry and Catalysis*

External surfaces

- Surface concentration → estimated from the bulk density

molecular density per cm^3, ρ → surface concentration per cm^2 σ,

$$\sigma = \rho^{2/3}$$

e.g., 1 g/cm^3 → $\rho \sim 5 \times 10^{22}$ → $\sigma \sim 10^{15}$ molecules cm^{-2} ($10^{19}/m^2$)

- Clusters and small particles

Dispersion

$$D = \frac{\text{number of surface atoms}}{\text{total number of atoms}} \quad (1.1)$$

Somorjai

volume of cluster $\sim d^3$, surface area $\sim d^2$ → $D \propto 1/d$ (inverse of the cluster size)

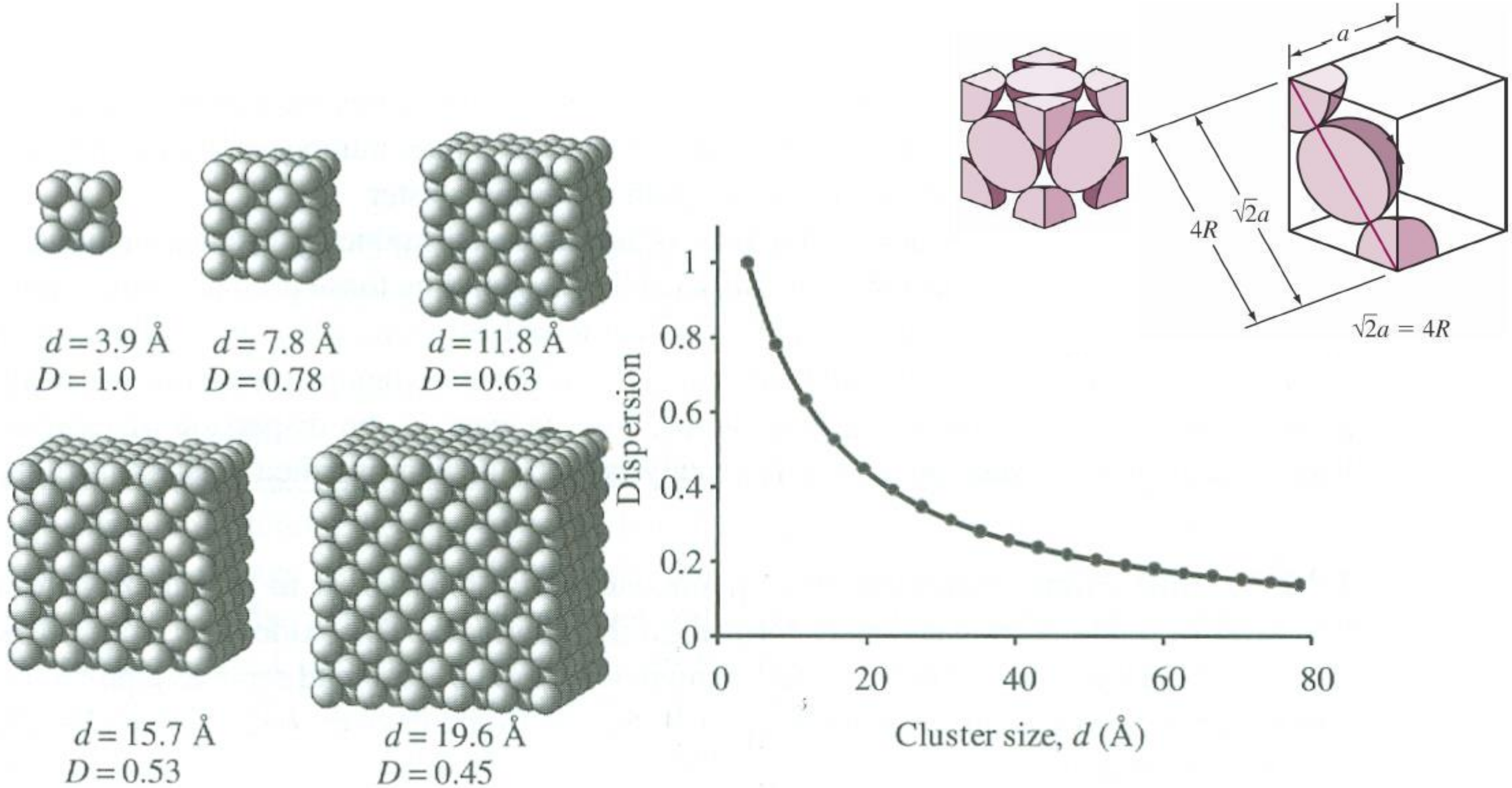


Figure 1.7. Cubic clusters with the face-centered cubic (fcc) packing of 14, 50, 110, 194, and 302 atoms (the left panel). In the smallest cluster, all of the atoms are on the surface. However, the dispersion defined as the number of surface atoms divided by the total number of atoms in the cluster, declines rapidly with increasing cluster size, which is shown in the right panel of the figure. The size d is the length of the edge of the cubic clusters. The lattice constant of the fcc clusters is assumed to be 3.9 Å, which is close to that of the Pt crystal.

10 nm size → D~0.1 surface (~10%)

Somorjai, *Introduction to Surface Chemistry and Catalysis*

- D depends somewhat on the shape of the particle and how the atoms are packed: the spherical cluster has smaller surface area than the cube cluster → lower dispersion (D) in round shape
- Higher D in catalysts → higher surface, lower the material cost

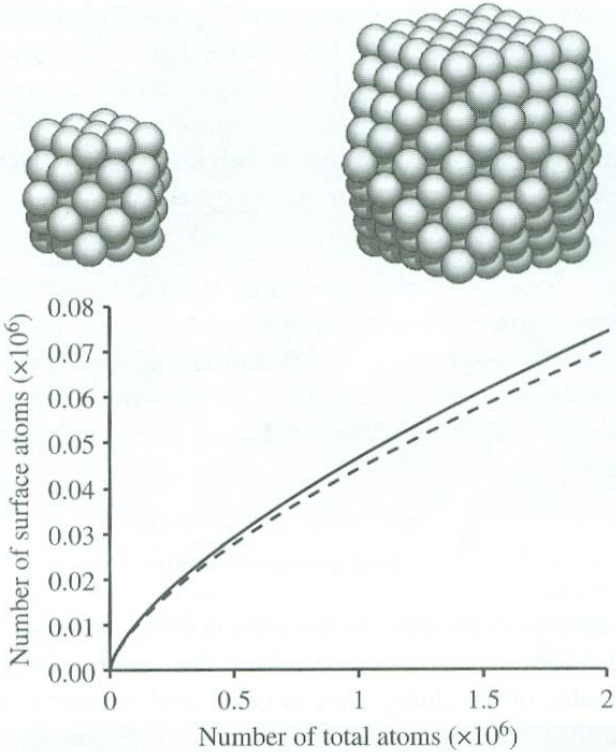


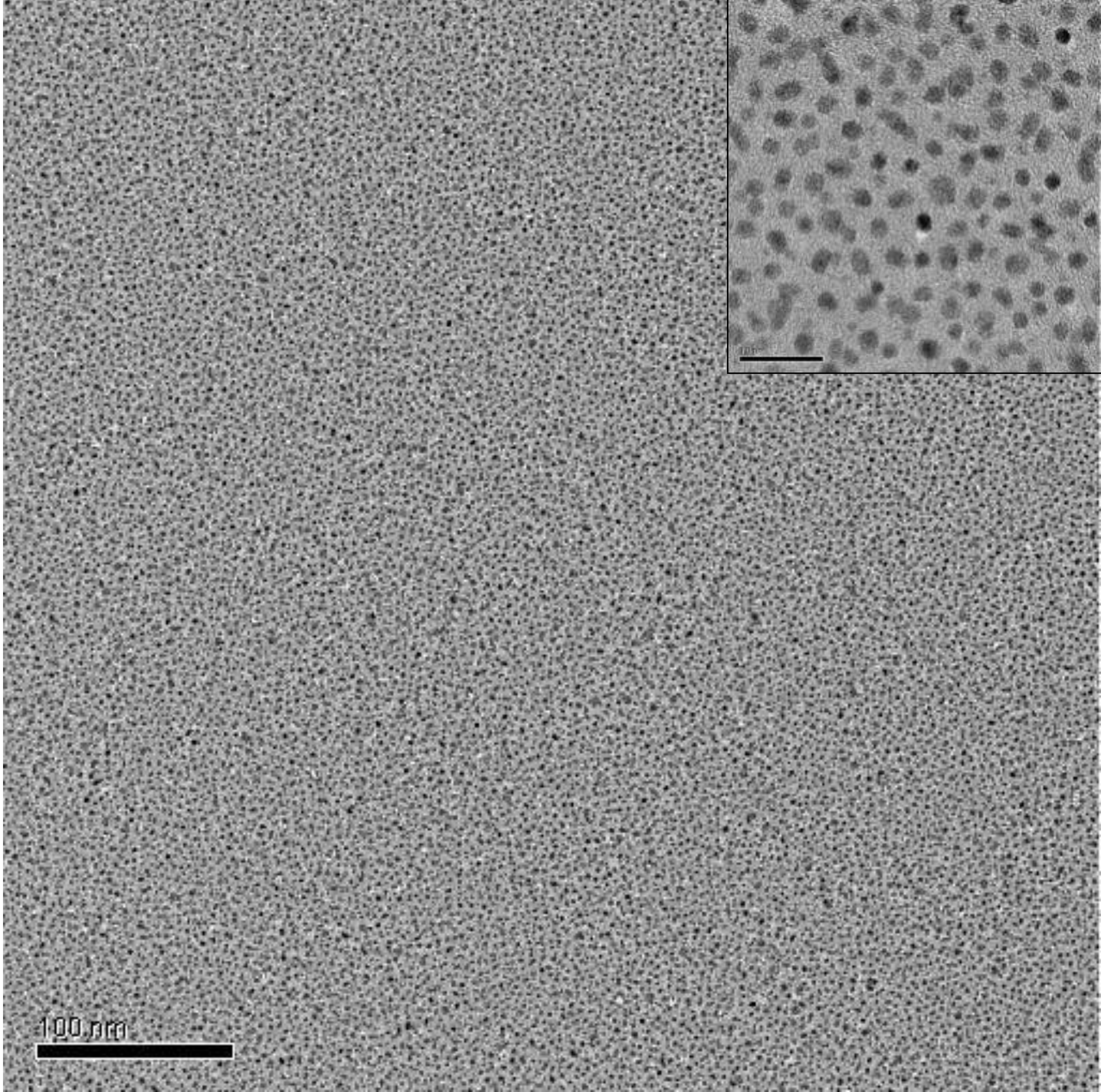
Figure 1.8. Truncated cubic clusters with the fcc packing of 55 and 309 atoms (the upper panel). The lower panel shows the number of surface atoms as a function of the total number of atoms for the cubic cluster (the solid line) and the truncated cubic cluster (the dashed line). Compared to the cubic cluster, the truncated cubic cluster is relatively rounder, so it has fewer atoms on the surface.

Brain
Leaf for photosynthesis
Thin film
Nanoparticle
Nanostructure….

Somorjai

Pt

Nanoparticle

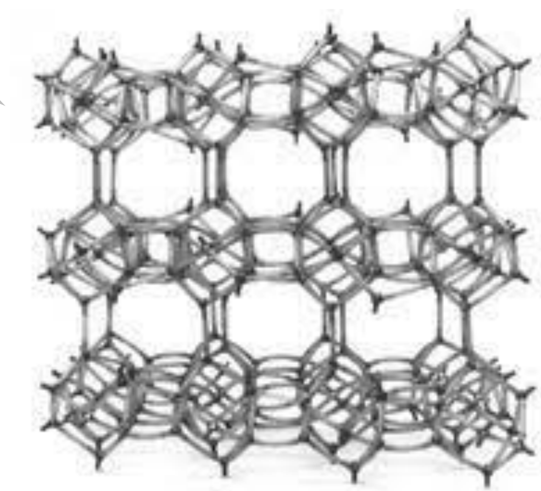


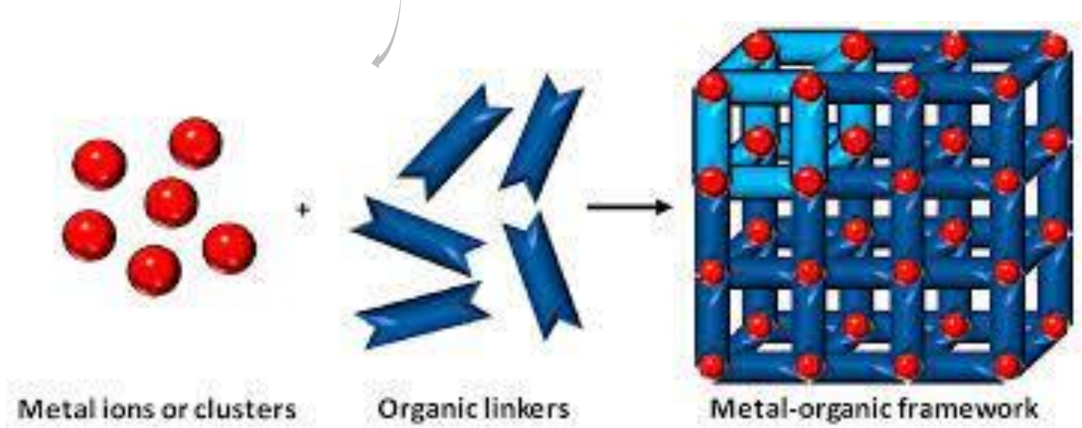
Sung's Lab

- Thin films: of great importance to many real-world problems and surface science

Internal surfaces: microporous solids

- Clays, graphite: layers → intercalation (for battery, filter, absorbent etc)
- Zeolites, MOFs(metal-organic frameworks): ordered cages of molecular dimensions → large surface area





Surface science & catalysis

- Catalysis: basis of chemical industry → billions of dollars of economic activity
- "Catalysis", Greek "wholly loosening" (κατα + λνσις): it takes part in a reaction but is not consumed → changing activation barrier → speed up a reaction (but, not change equilibrated state) & perform selectively for the desired product

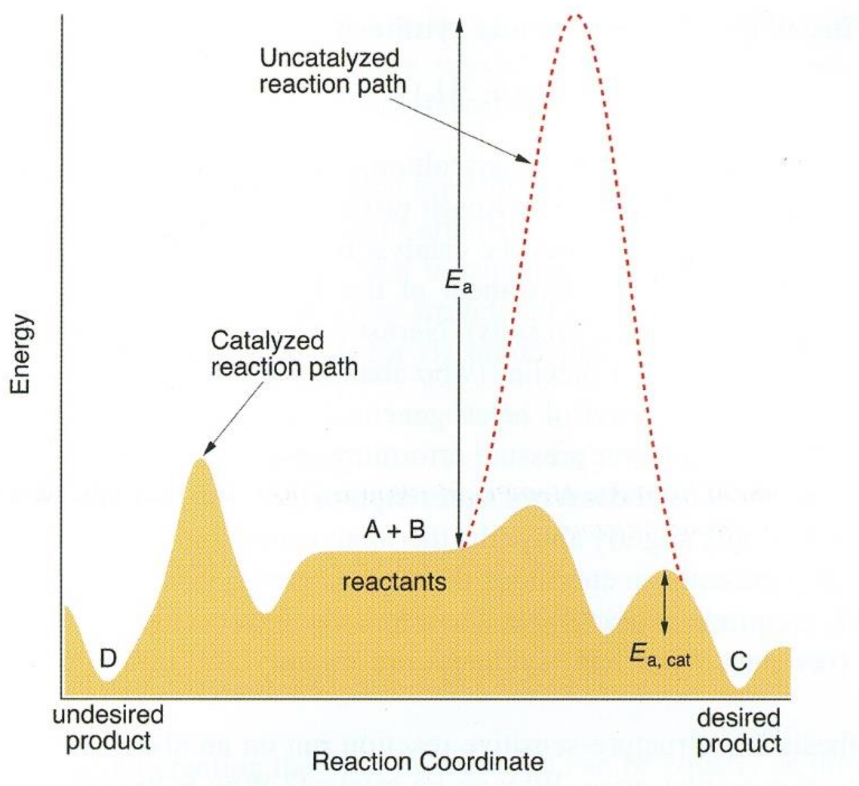


Fig.1.2. Kolasinski

Why surfaces and interfaces?

- Ammonia synthesis

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

Nitrogen fertilizers underpin modern agriculture [6]. The inexpensive production of fertilizers would not be possible without the Haber-Bosch process. Ammonia synthesis is almost exclusively performed over an alkali metal promoted Fe catalyst invented by Haber, optimized by Mittasch and commercialized by Bosch. The establishment of the Haber-Bosch process is a fascinating story [6]. Ostwald (who misinterpreted his results), Nernst (who thought yields were intolerably low and abandoned further work), and Le Châtelier (who abandoned his work after an explosion in his lab), all could have discovered the secret of heterogeneously catalysed ammonia synthesis but did not. Technical innovations such as lower pressure reforming and synthesis, better catalysts and integrated process designs have reduced the energy consumption per ton of fixed nitrogen from 120 GJ to roughly 30 GJ, which is only slightly above the thermodynamic limit. This factor of four improvement in energy efficiency represents an enormous decrease in energy usage since over 140 million metric tons (MMt) of NH_3 are produced each year. Therefore, the improvement also represents a tremendous decrease in cost (revenues from NH_3 synthesis are roughly \$60 billion annually) as well as CO_2 release.

Ammonia synthesis is a structure-sensitive reaction run on an alkali metal promoted Fe catalyst. Already a number of questions arise. Why an Fe catalyst? Why is the reaction run at high pressure and temperature? What do we mean by promoted, and why does an alkali metal act as a promoter? What is a structure sensitive reaction? What is the reforming reaction used to produce hydrogen, and how is it catalysed? By the end of this book all of these answers should be clear.

However, consideration of NH_3 as merely a precursor to fertilizer may be too limited a conception. NH_3 could also constitute an energy carrier that does not emit CO_2 upon combustion. To realize this potential of NH_3 we would need to master an electrochemical route to NH_3 that generates the required H atoms from a non-hydrocarbon based source. The ideal electrochemical cell would encompass the reactions

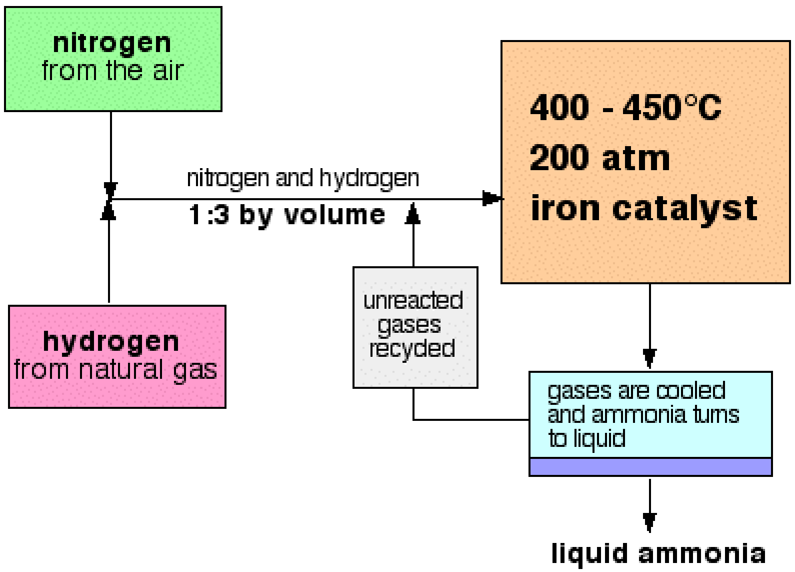
$$6H_2O(l) + 2N_2(g) \rightarrow 3O_2(g) + 4NH_3(g).$$

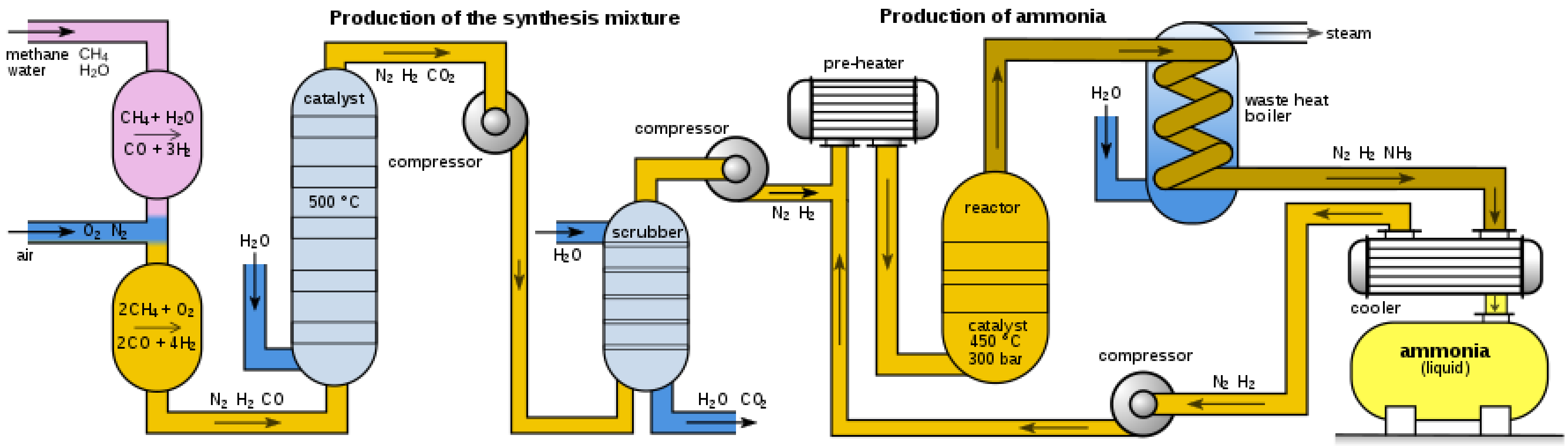
If the electrical current required to drive this electrolytic reaction can be generated renewably through, e.g. wind turbines or photovoltaic cells, then the NH_3 constitutes a carbon neutral energy carrier. This section should convince you that applications of surface science lie at the heart of the Energy-Water-Food Nexus [9].

Kolasinski

Haber Process

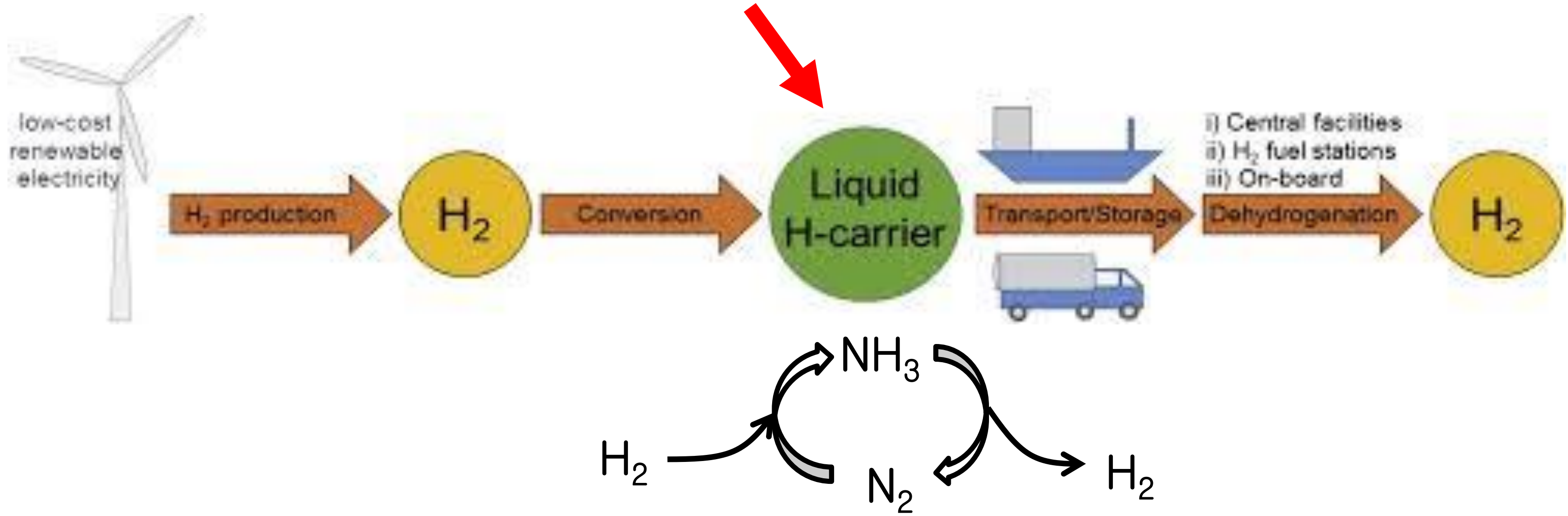
Nobel Prize in Chemistry (1918)





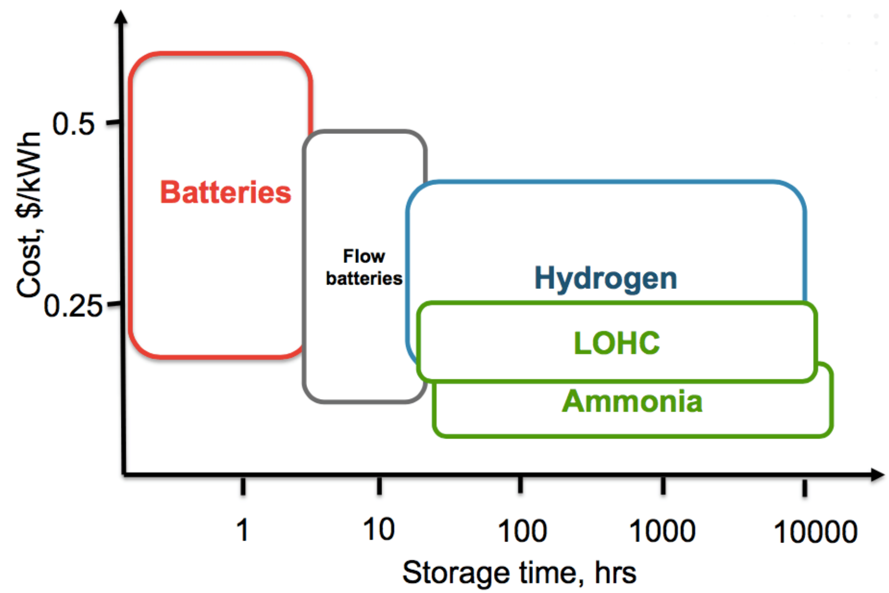
From Wikipedia

NH_3: a carbon neutral energy carrier



LOHC	wt.% of H	Energy Density (kWh/L)
Liquid Hydrogen	100	2.5
Ammonia	17.8	3.6
Gasoline	16.0	9.7
Biodiesel	14.0	9.2
Methanol	12.6	4.7
Ethanol	12.0	6.3
Formic Acid	3.4	2.1
Hydrazine Hydrate	8.1	5.4

G.Soloveichik, Beilstein *J. Nanotechnol.* 5,1399 (2014)



Arpa-e program, DOE, USA (2016)

Gerhard Ertl, Nobel Prize in Chemistry (2007)

Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany
Prize motivation: “for his studies of chemical processes on solid surfaces”

Work
Often, chemical reactions are speeded up by surfaces, as in the case when gaseous molecules come in contact with a metal surface. During the 1960s Gerhard Ertl developed a number of methods for studying surface chemical reactions. Among other things, he made use of techniques for producing a very pure vacuum, which had been developed within the semiconductor industry. Ertl was able to map out details of a process of great importance in the production of artificial fertilizer: the Haber-Bosch process in which nitrogen in the air is converted to ammonia via an iron catalyst.

- Gas-to-liquids: Fischer-Tropsch synthesis, C1 chemistry, artificial photosynthesis

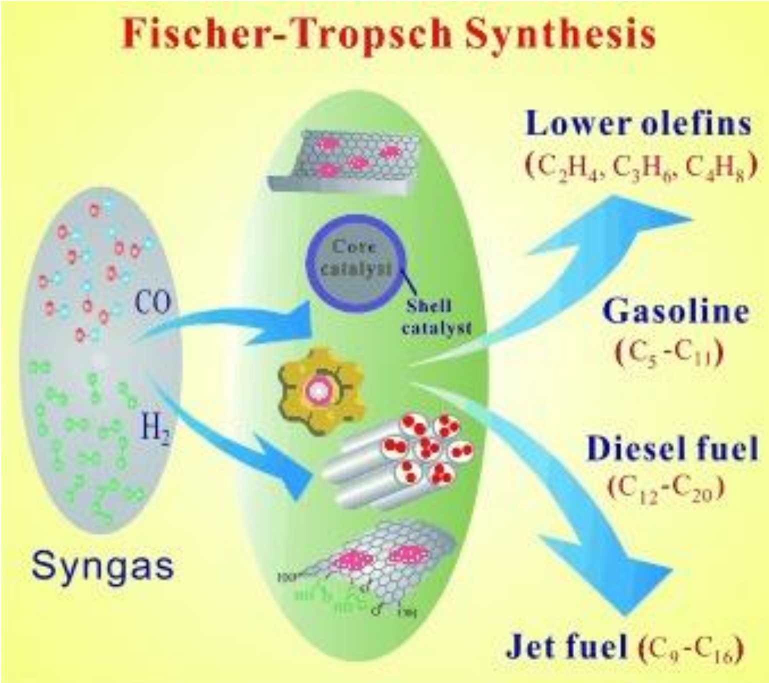
$$H_2 + CO \rightarrow \text{liquid hydrocarbons (HC) and oxygenates (Fischer – Tropsch)}$$

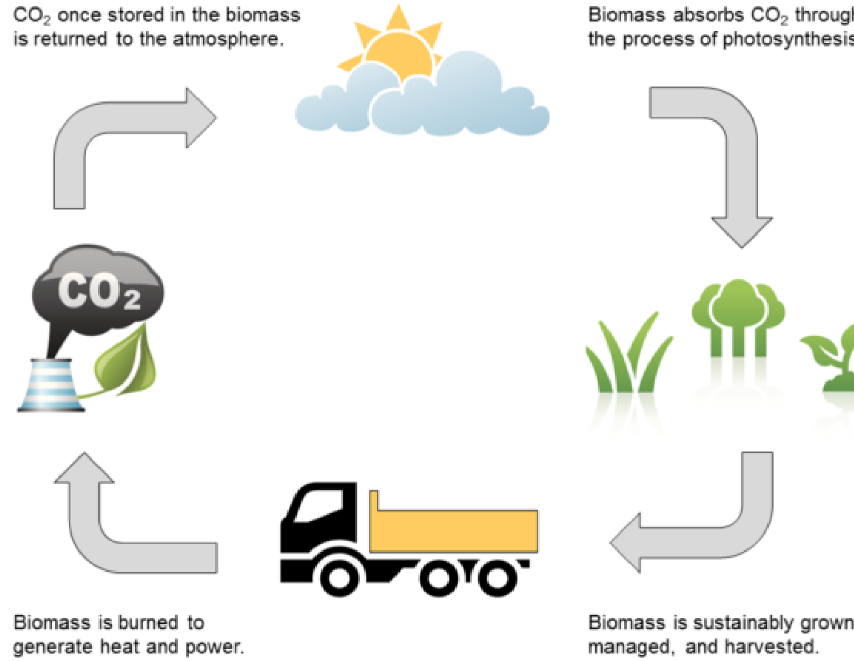
$$CO, CO_2, CH_4, CH_3OH + \ \ldots \ \rightarrow \text{liquid hydrocarbons (C1 chemistry)}$$

$$H_2O + CO_2 \rightarrow \text{liquid hydrocarbons (artificial photosynthesis)}$$

-Transforming natural gas & coal
- Biomass
- Artificial photosynthesis: a branch of photocatalysis, H_2 production, CO_2 conversion, solar fuels

Source: UABIO.org





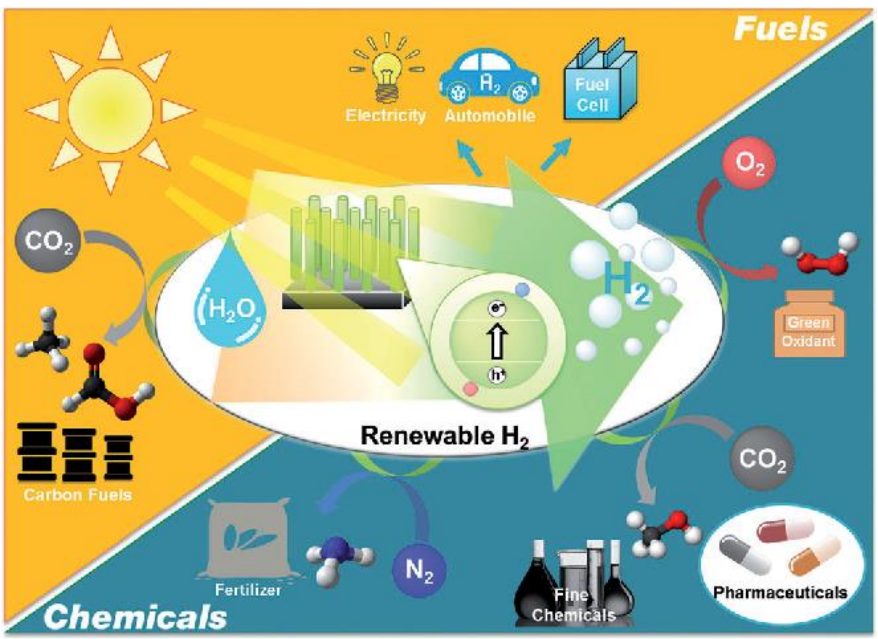


Figure 1. The role of artificial photosynthesis in green chemistry.

Peidong Yang group, *Angew Chem Int. Ed.*, **2015**, 54, 3259

- Clean propulsion: three-way catalyst, batteries, fuel cells

$$NO_x, CO, \text{and } HC \rightarrow H_2O + CO_2 + N_2$$

$$Li^+ \text{ (or } Na^+, \text{ or } Mg^{2+}) \rightarrow \text{intercalation/lattice insertion}$$

$$H_2(g) \text{ (or } NH_3(g)) + O_2(g) \rightarrow H_2O(g) \ (+N_2(g))$$

- reduce pollution, (ultra)fine particle (PM 2.5, particulate matter)
- batteries, photovoltaics, fuel cells, thermoelectrics: surface, interface, pores

- Water splitting: oxygen and hydrogen evolution reaction (OER, HER)

a fundamental understanding of interfacial electron transfer. The splitting of water

$$2H_2O(l) \rightarrow O_2(g) + 2H_2(g)$$

is related to two related half-reactions; namely, the oxygen evolution reaction (OER)

$$2H_2O(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^- \text{ (OER)}$$

and the hydrogen evolution reaction (HER)

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \text{ (HER)},$$

which in acid solutions reduces to

$$2H^+(aq) + 2e^- \rightarrow H_2(g).$$

- Surface chemistry: semiconductor processing and nanotechnology

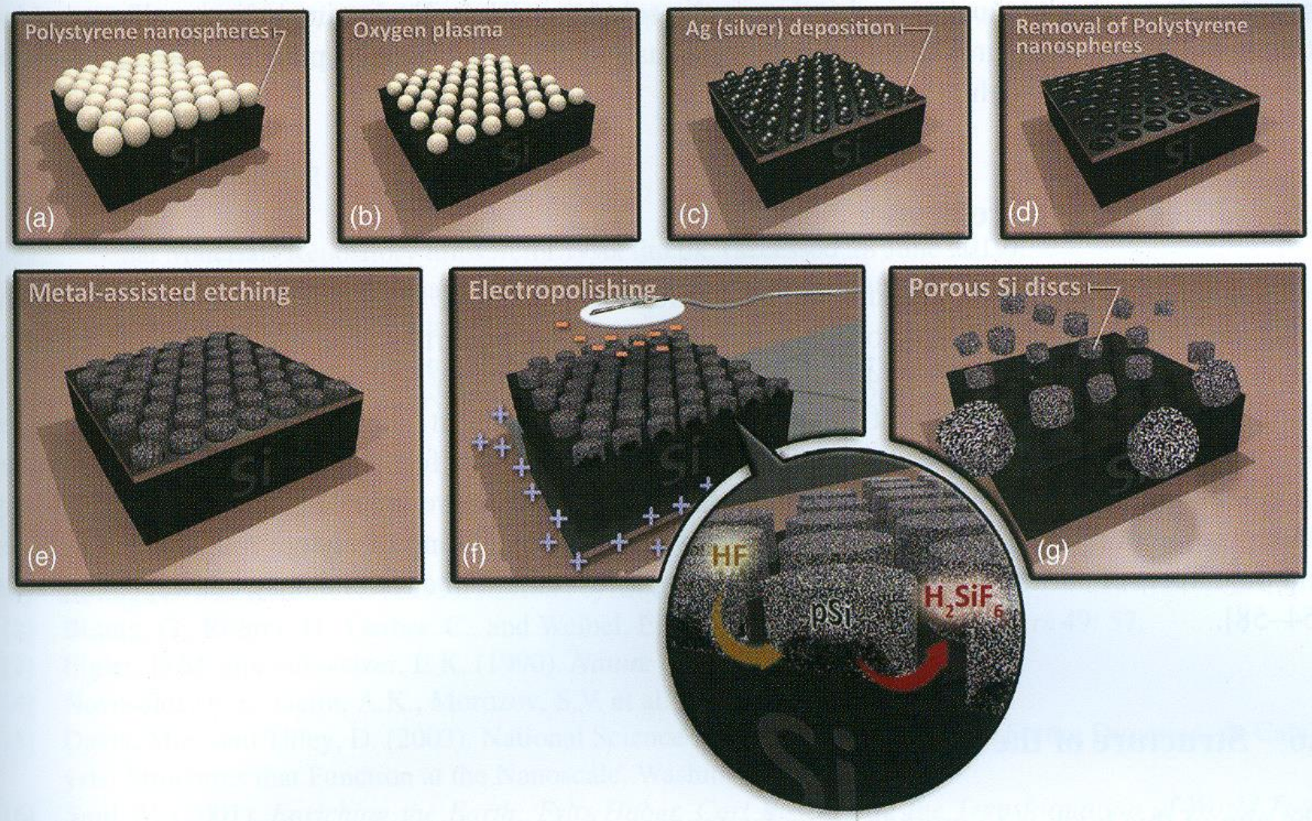


Figure I.3 An example of the self-assembly, growth and etching processes used to create a hierarchically structured nanomaterial. (a) Self-assembled growth of a polystyrene nanosphere monolayer on a Si substrate. (b) Etching with oxygen plasma to reduce the size of the nanospheres. (c) Deposition and growth of a thin film of Ag. (d) Dissolution of polystyrene to reveal an ordered array of holes in the Ag thin film. (e) Etching of Si in a $H_2O_2 + HF$ solution creates Si disks porosified with nanoscale pores. (f) Electrochemical etching at the bottom of the disks to release them from the substrate as shown in panel (g). Source: Reproduced with permission from H. Alhmoud, B. Delalat, R. Elnathan, A. Cifuentes-Rius, A. Chaix, M.-L. Rogers, J.-O. Durand, N. H. Voelcker, Adv. Func. Mater., **25** (2015) 1137. © 2014 Wiley-VCH.

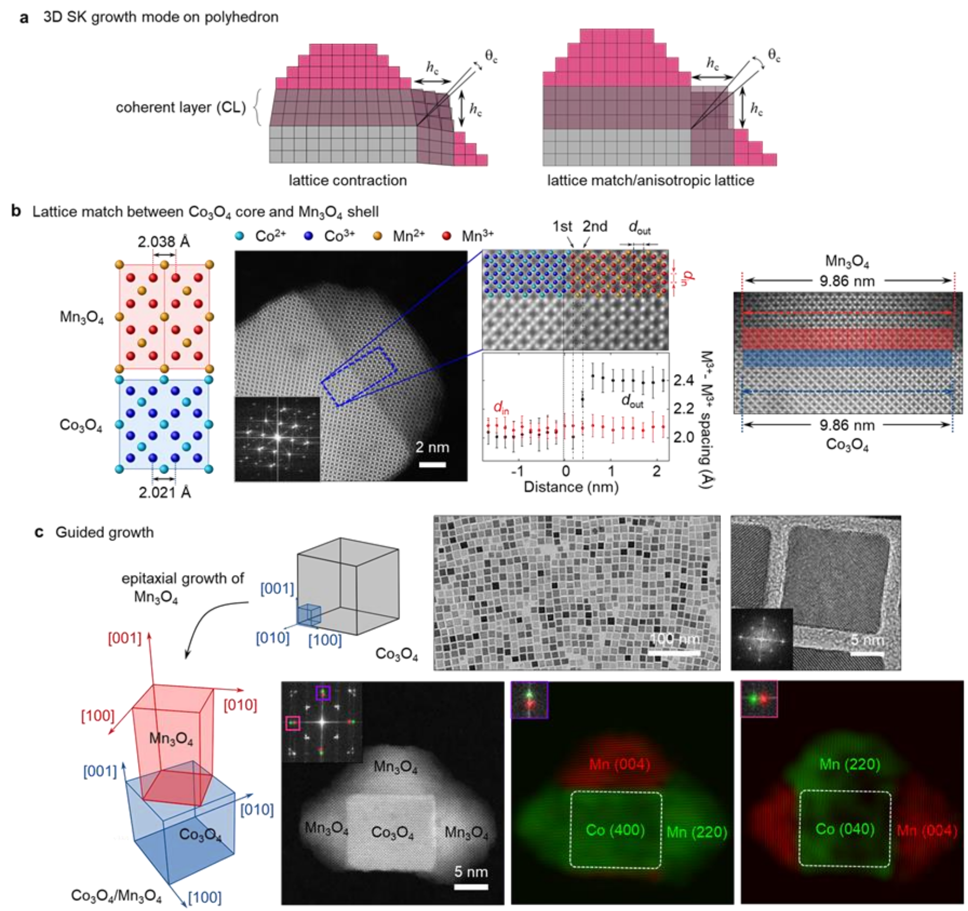
Large interface-to-volume ratio

- Nanotechnology

Article

Design and synthesis of multigrain nanocrystals via geometric misfit strain

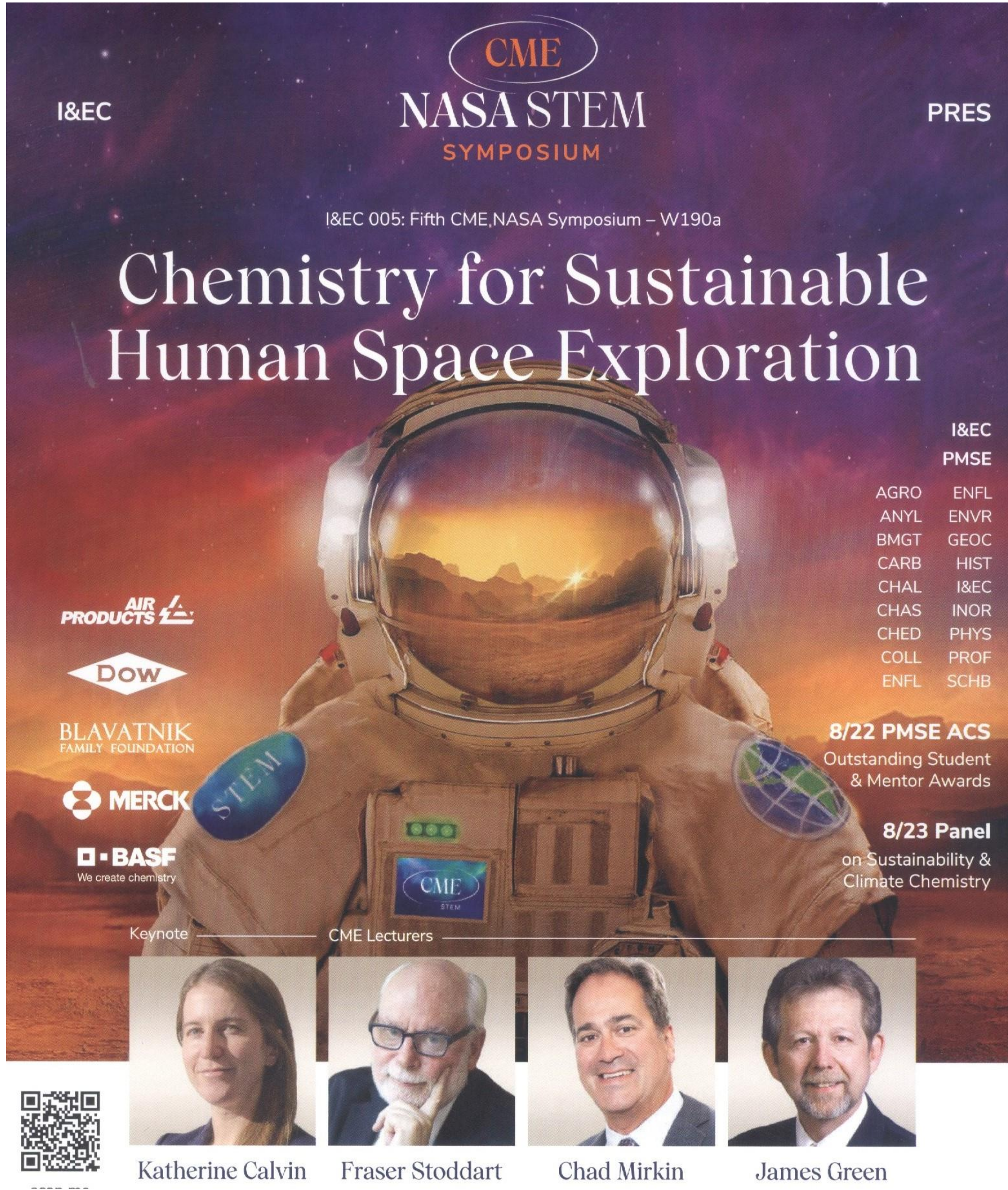
Myoung Hwan Oh[1,2,3,4,5,13], Min Gee Cho[1,2,5,13], Dong Young Chung[1,2], Inchul Park[1,6], Youngwook Paul Kwon[7], Colin Ophus[8], Dokyoon Kim[1,2,9], Min Gyu Kim[10], Beomgyun Jeong[11], X. Wendy Gu[12], Jinwoung Jo[1,2], Ji Mun Yoo[1,2], Jaeyoung Hong[1,2], Sara McMains[7], Kisuk Kang[1,6], Yung-Eun Sung[1,2], A. Paul Alivisatos[3,4,5,14]* & Taeghwan Hyeon[1,2,14]*



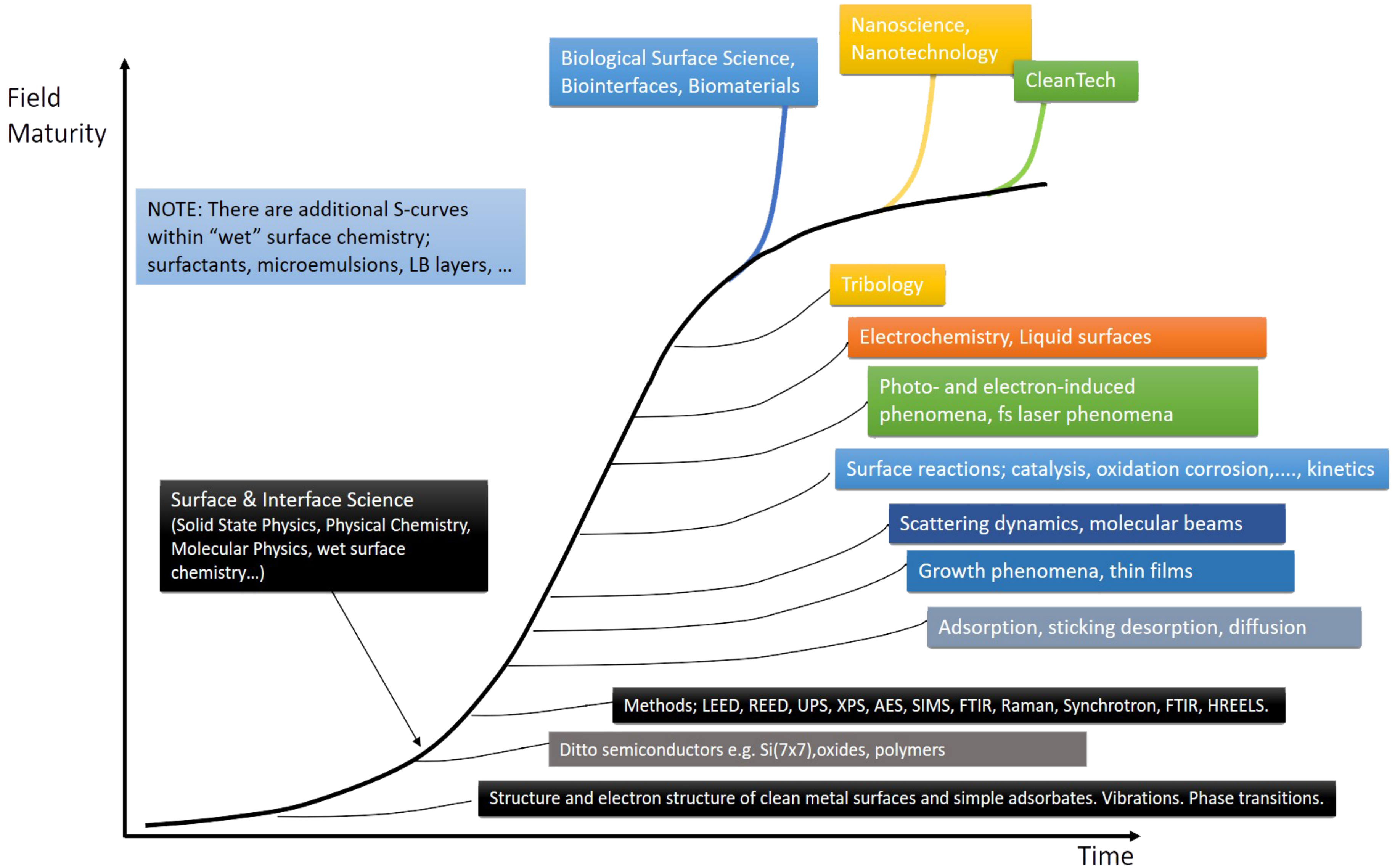
Nature **2020**, *577*, 359-363.

Surface science for sustainability

Surface science for space age



Surface science perspectives



Source: Prof. Bengt Kasemo, Biolin Scientific

Structure of this course

Surface & adsorbate structure: geometric, electronic, vibrational

Experimental probes and techniques

Chemisorption, physisorption, and dynamics

Thermodynamics and kinetics of adsorption and desorption

Thermodynamics of surface and interface

Liquid interfaces: surface tension, surfactant, an so on

Application to catalysis and nanoscience

Enjoy this course!