Global Focus on Knowledge

Production and Application of Materials

The University of Tokyo   Hiroshi Komiyama

Lecture One: The production process of matter, e.g., metals (iron and steel).

Lecture Two: Conjugation (device), e.g., semiconductors and inorganic materials.

Lecture Three: Soft matter, e.g., liquid crystals.

Lecture Four: Matter in durable earth (device), e.g., fuel cells and biochips.

Population

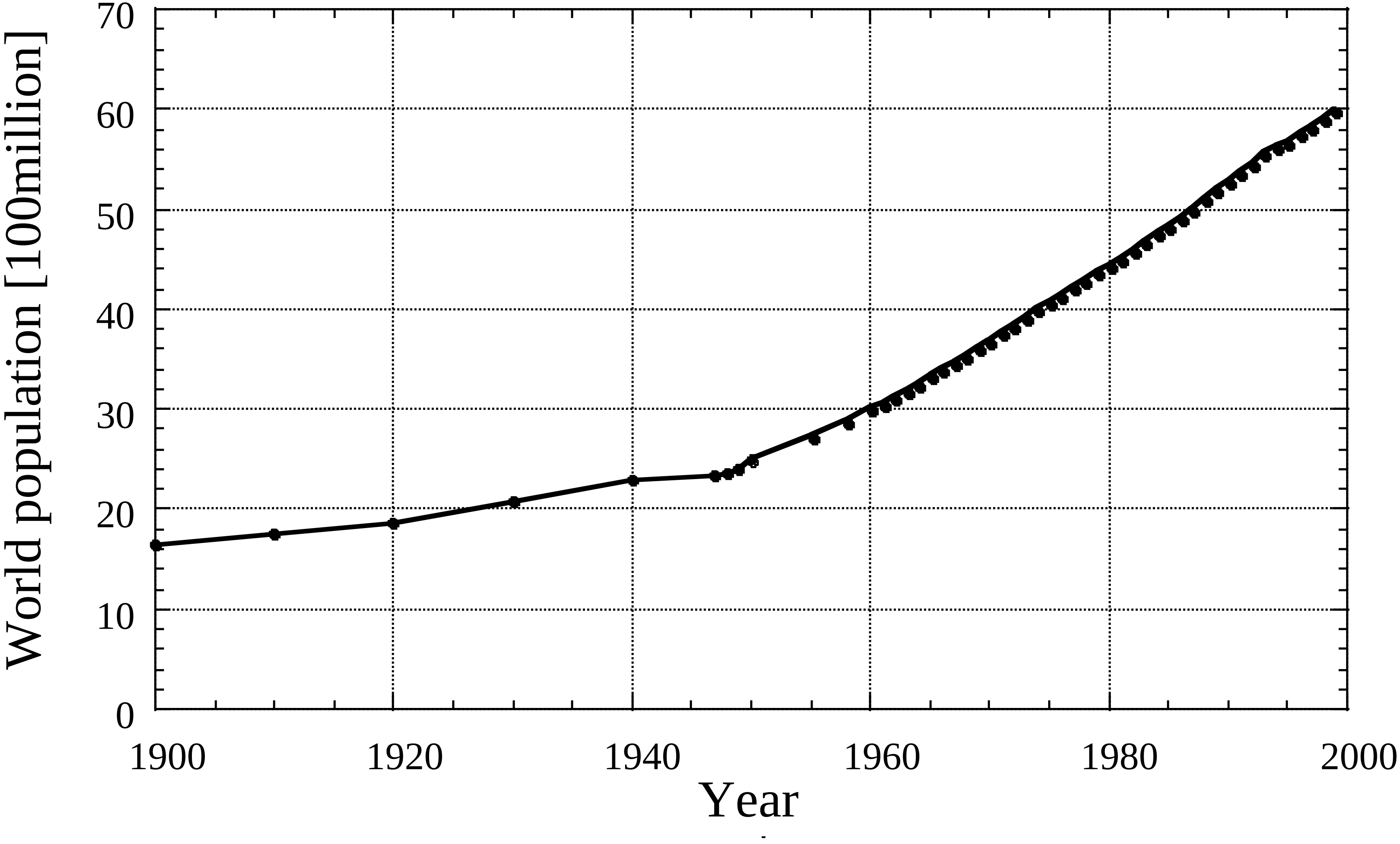


Figure: Transition of the world's population in the 20th century.
(Sources from Statistical Yearbook, U.S. Department of the State, and United Nations estimation.)

Iron and Steel

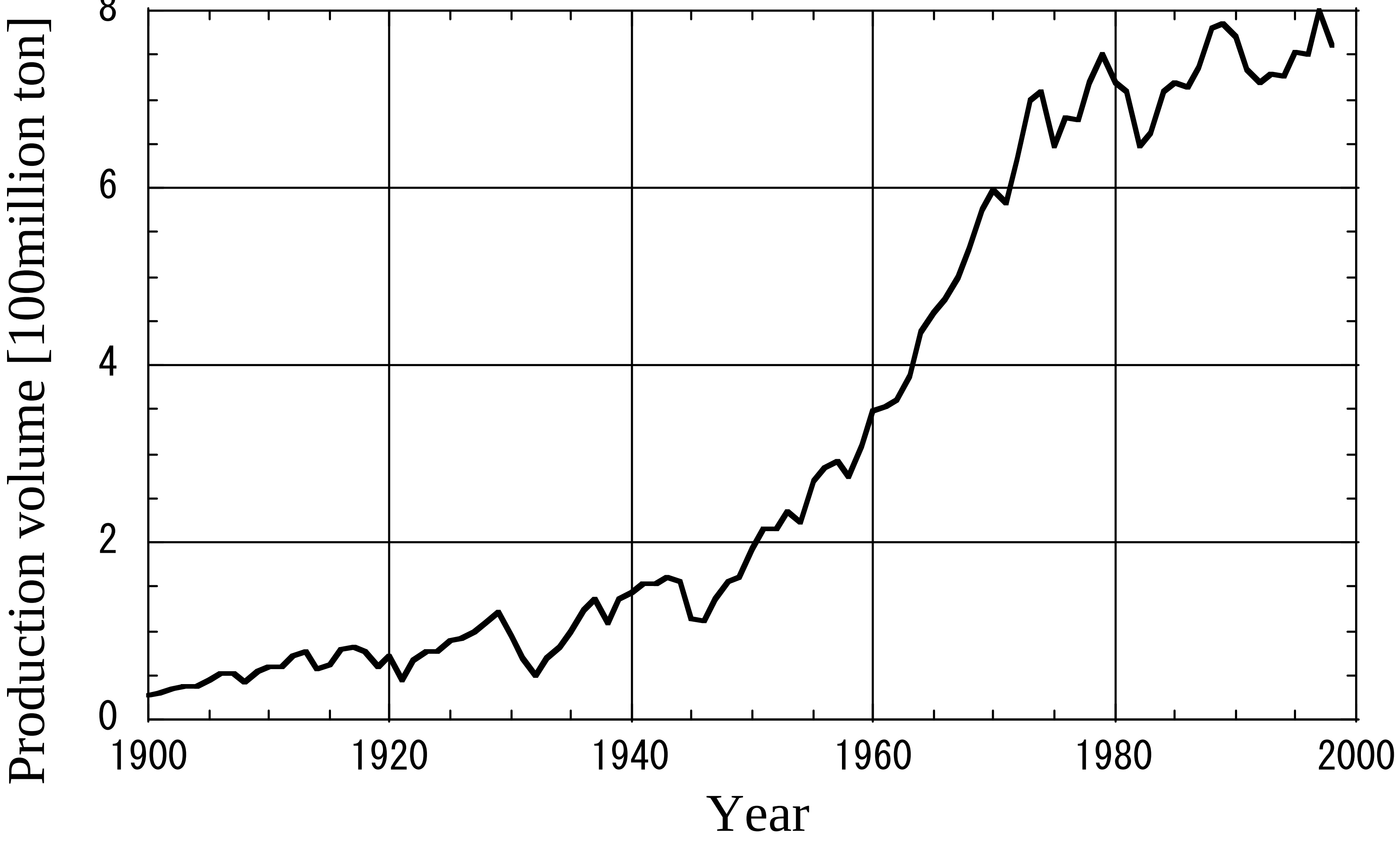
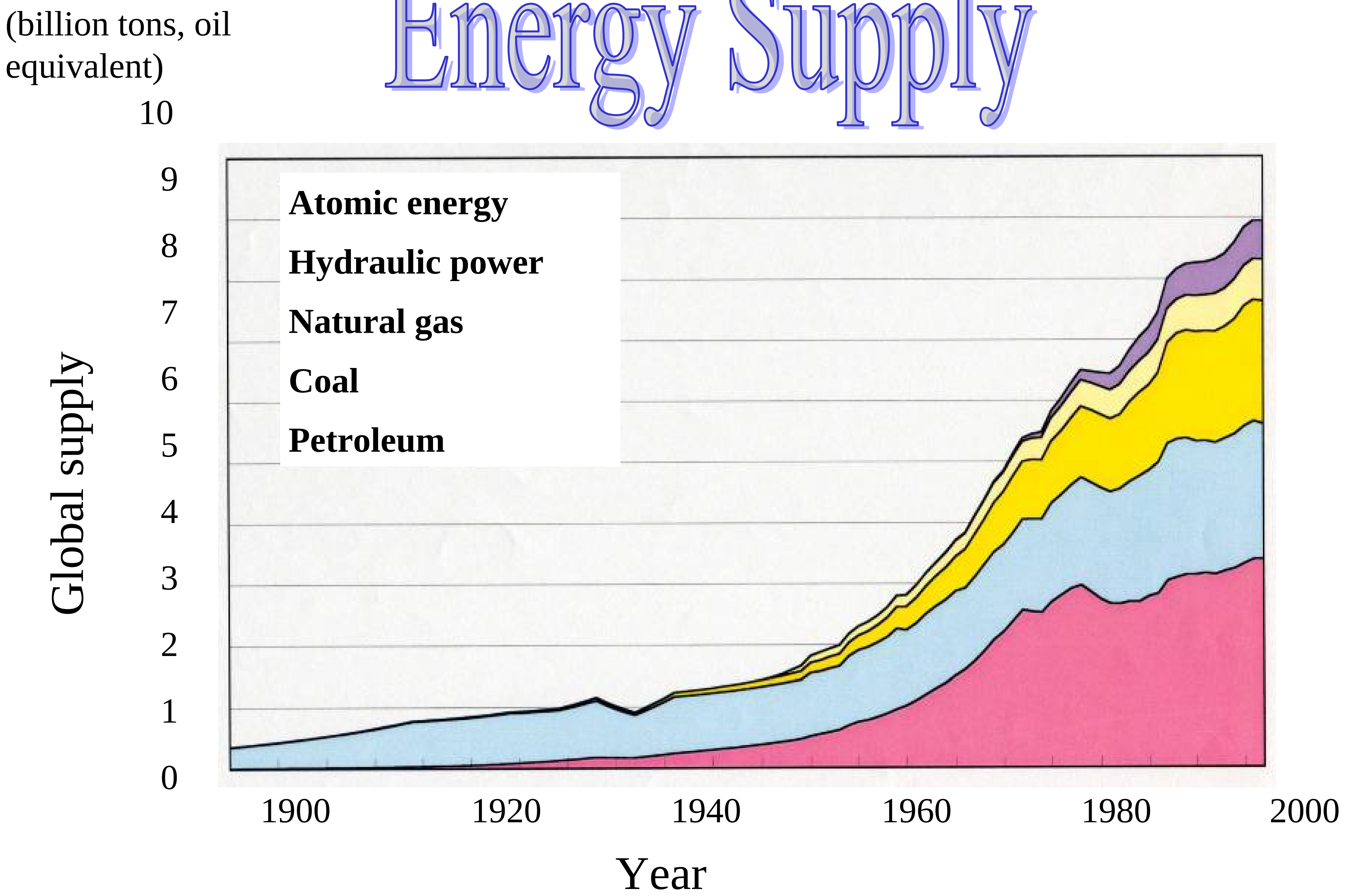


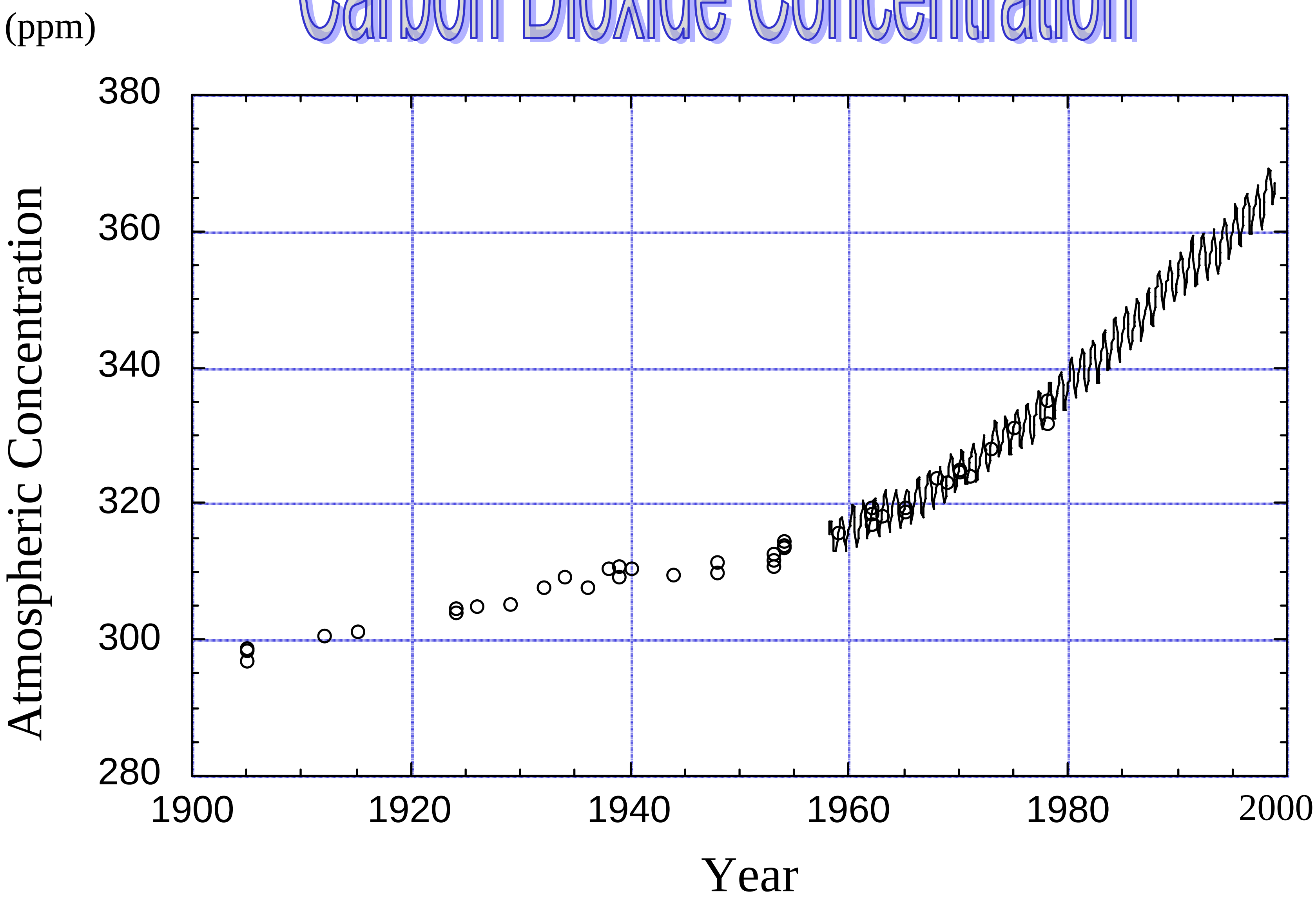
Figure 2: Global production volume of crude steel and pig iron.
(Sources from Statistical Yearbook and International Historical Statistics.)

Energy Supply



Sources: UN Statistical Yearbook, BP Statistical Review of the World Energy

Carbon Dioxide Concentration



Source: National Oceanic and Atmospheric Organization

20th Century: it was the century of expanding human activities.

21st Century: it is the century to accomplish a sustainable society.

What is the role of science and technology?

Energy

Energy resources: primary energy

Energy: secondary energy

E.g., electricity, hydrogen, and gasoline

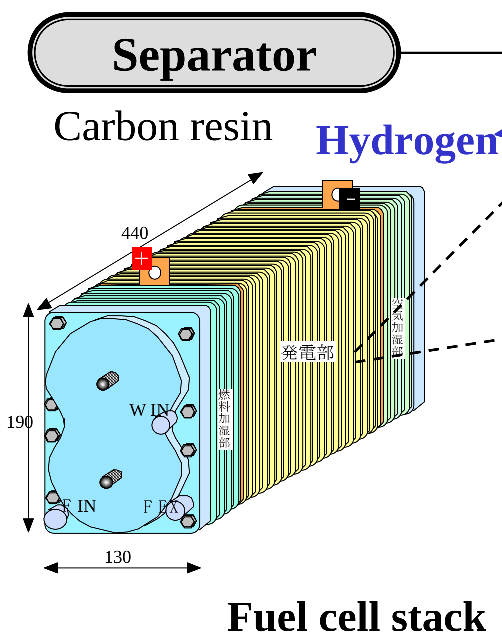
Conversion efficiency:

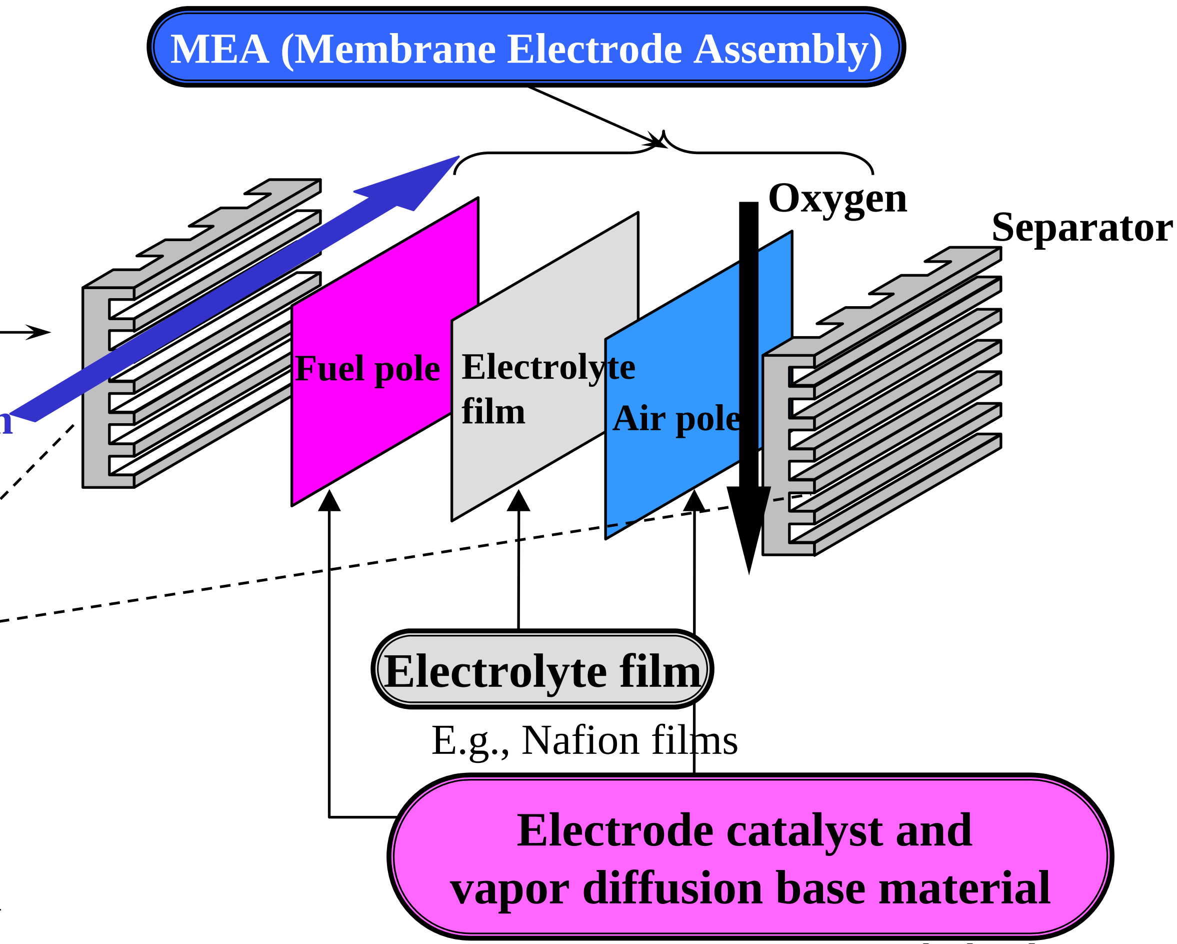
power generation and petroleum refining

Utilization efficiency:

steel manufacturing, automobiles, and refrigerators

Fuel Cell System and Materials



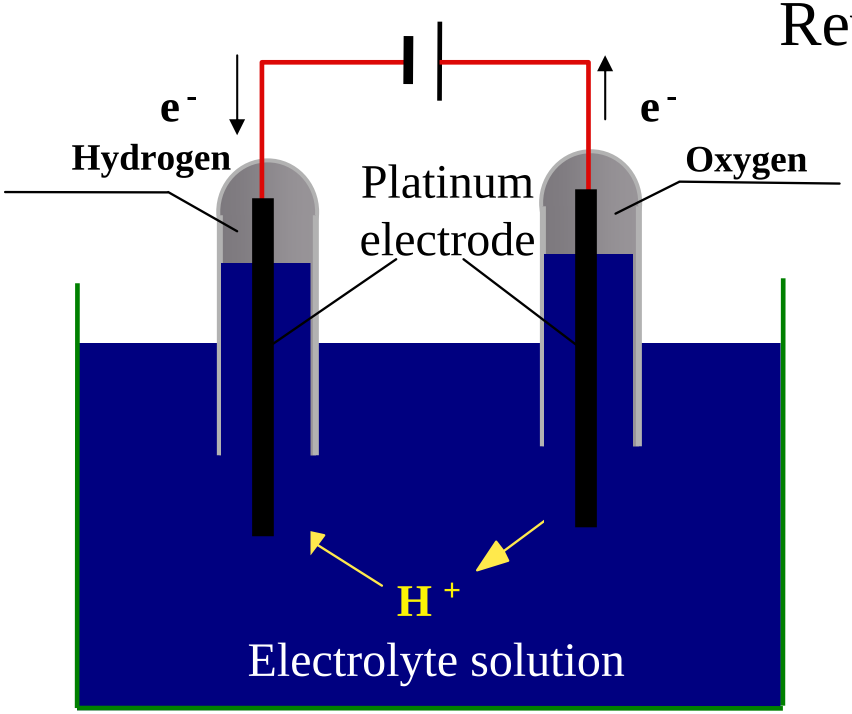


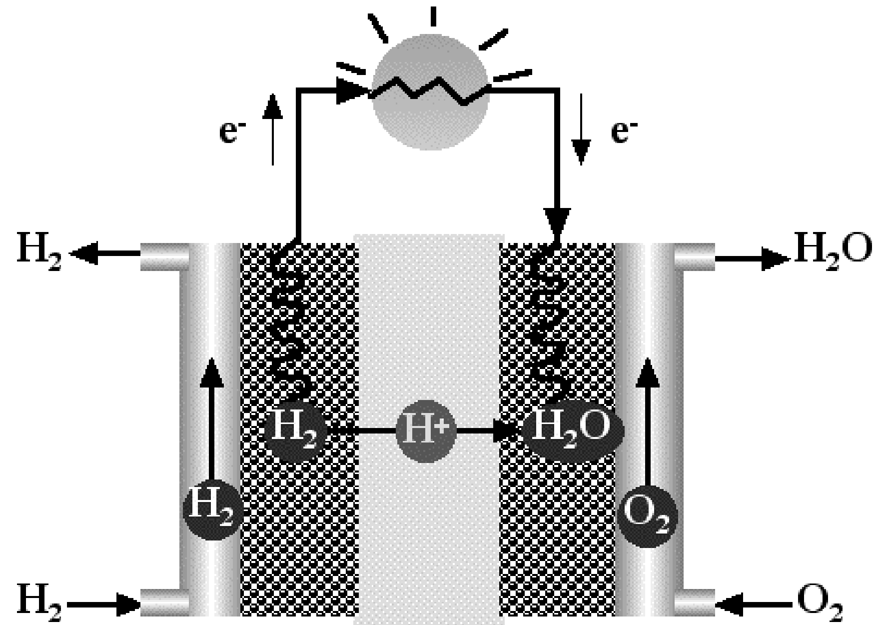
Sources: Mitsubishi Electric Corp.

Principles of Fuel Cells

Water electrolysis ⟷ Fuel cell

Reverse reaction





Greater than 1.2 V is required.

Electrochemical reaction

Hydrogen pole: $H_2 = 2H^+ + 2e^-$

Oxygen pole: $2H^+ + 1/2O_2 + 2e^- = H_2O$

Maximum Theoretical Efficiency

Water electrolysis
minimum1.2 [V]

Minimum energy = 1.2 [V] × Current [A]

If we can create a fuel cell that generates 2 [V],

$$H_2 + \frac{1}{2}O_2 \underset{1.2\,[V]}{\overset{2\,[V]}{\rightleftarrows}} H_2O$$

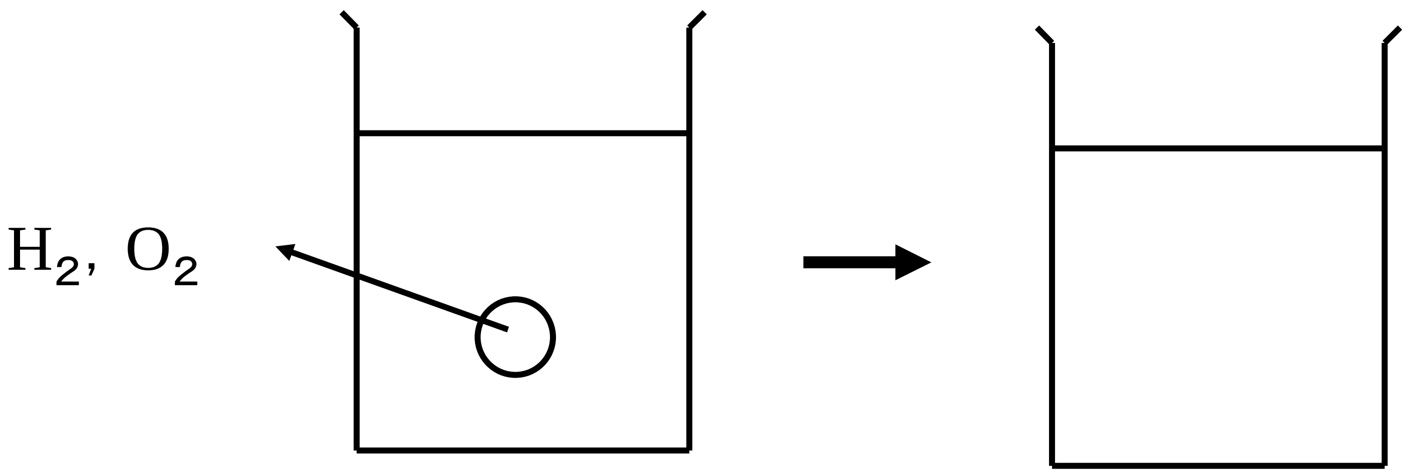
Single operation of water electrolysis and fuel cell can yield the energy of: 0.8 [V]×current

Which in fact violates the law of conservation of energy and matter→ it must be impossible.
Fuel cell of 1.2 [V] possesses the maximum energy conversion efficiency.

Zero Efficiency Process

1. A fuel cell with electromotive force of 0 volts

2. Ignite in water and simply keep burning



Ignition

Practically, there is no change.

Hydrogen and oxygen become 20℃.

Thermodynamics

Let us suppose, $H_2 + \frac{1}{2}O_2 = H_2O$ 25℃

What matters is the initial temperature (25℃) and final temperature (25℃).
The changes during the process do not have any effect in thermodynamics.

Energy generation rate ＝ Electric＋Shaft work＋Light＋Sound＋･･＋Heat

ΔH(constant) ＝ ΔG ＋ $T\Delta S$

↑

The maximum value of all work (excludes heat)!

Maximum theoretical efficiency $= \dfrac{\Delta G}{\Delta H}$

Whether it is the heat power generation or the fuel cells,
the maximum theoretical efficiencies stay the same.

Expectations for Fuel Cells

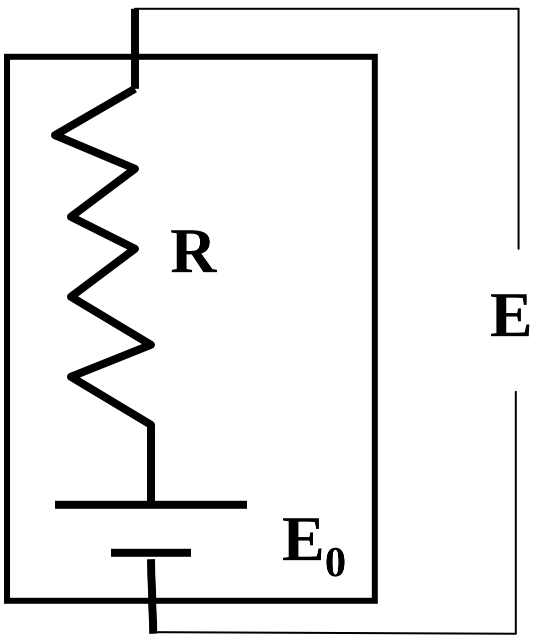
Power generation can be achieved by rotating the shaft of a generator. ←bicycles
Thermal power generation←the turbines are spinning via steam power and combustion gas.
←Ideal conditions can be obtained by increase of temperature.
Steam turbines: limit of steam temperature
Vapor turbines: limit in materials

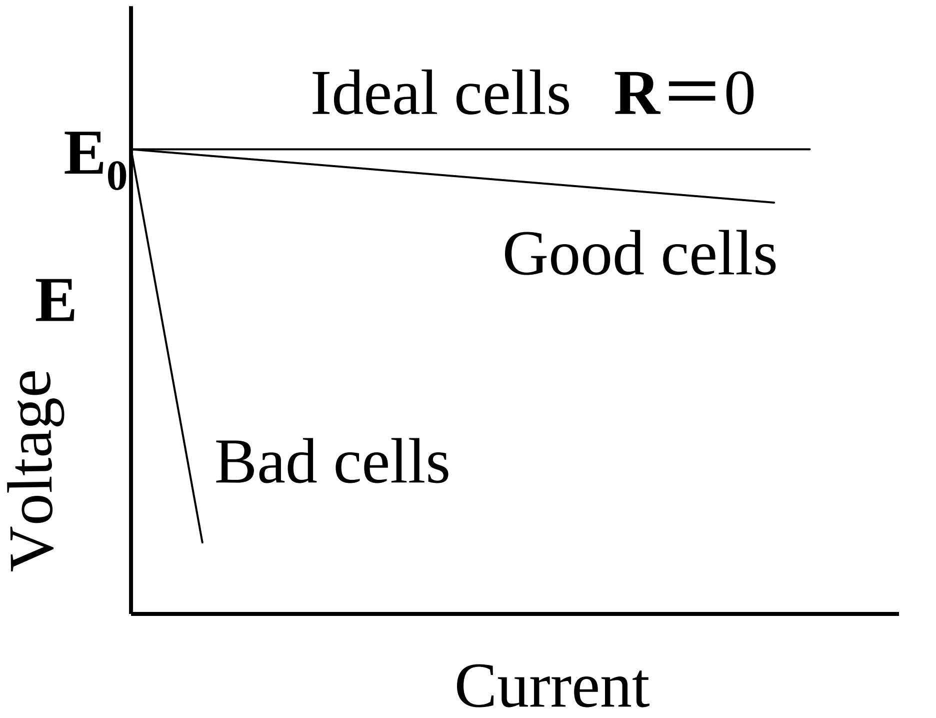
Fuel cells←There is no restriction of temperature because there is no heat conversion concerned in the reaction.

- Possibility of efficient power generation at low temperature.
- The solutions for efficiency improvement may become clear.
- Applications of miniaturizations, mobiles, dispersed stationary-types, and portable generators.

Be able to corresponds with the load fluctuation.

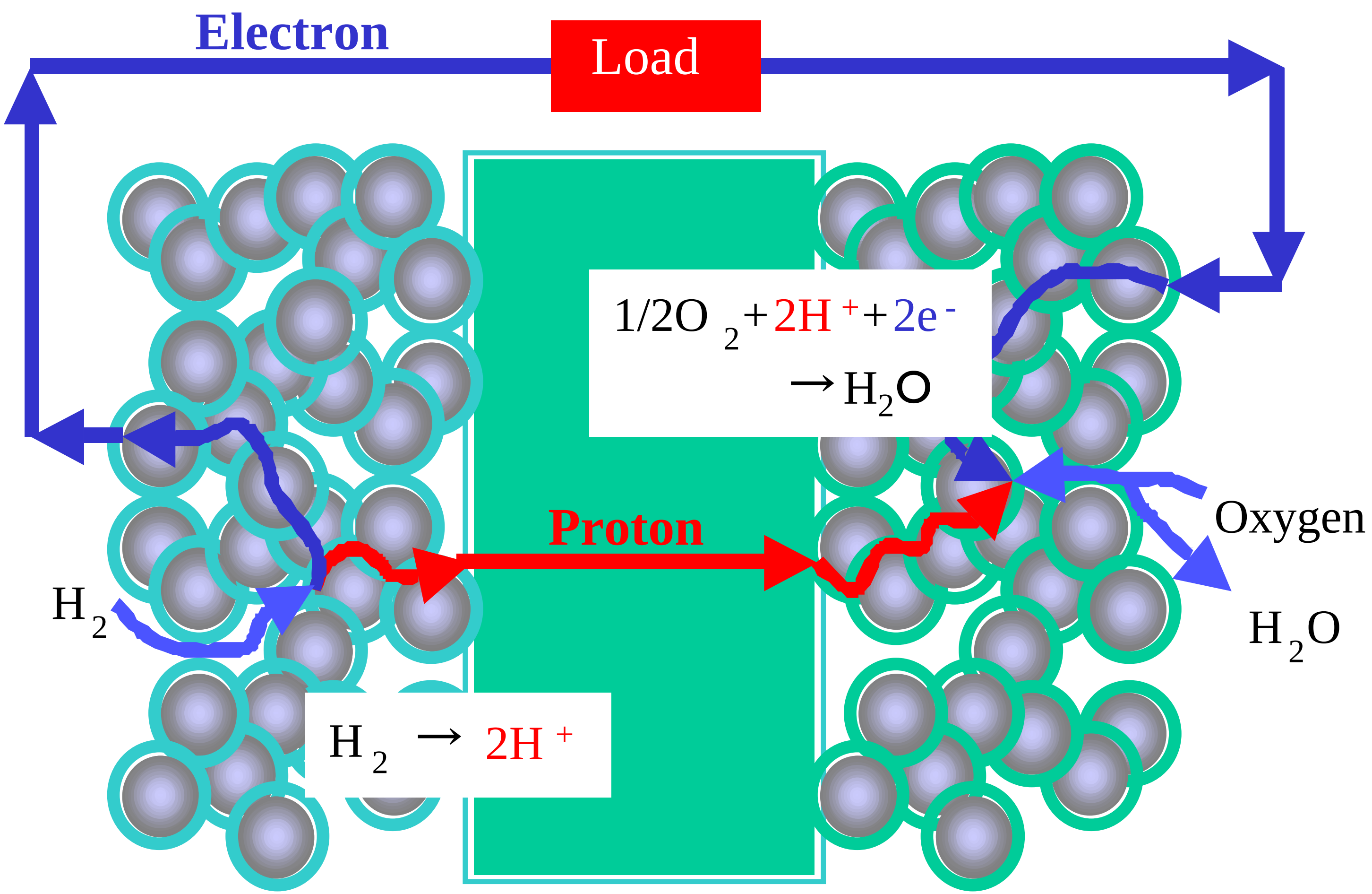
The Cause of Efficiency (E/E_0) Drop is Internal Resistance





Efficiency increase is expected if the electric current is not collected; however, it has no effect.

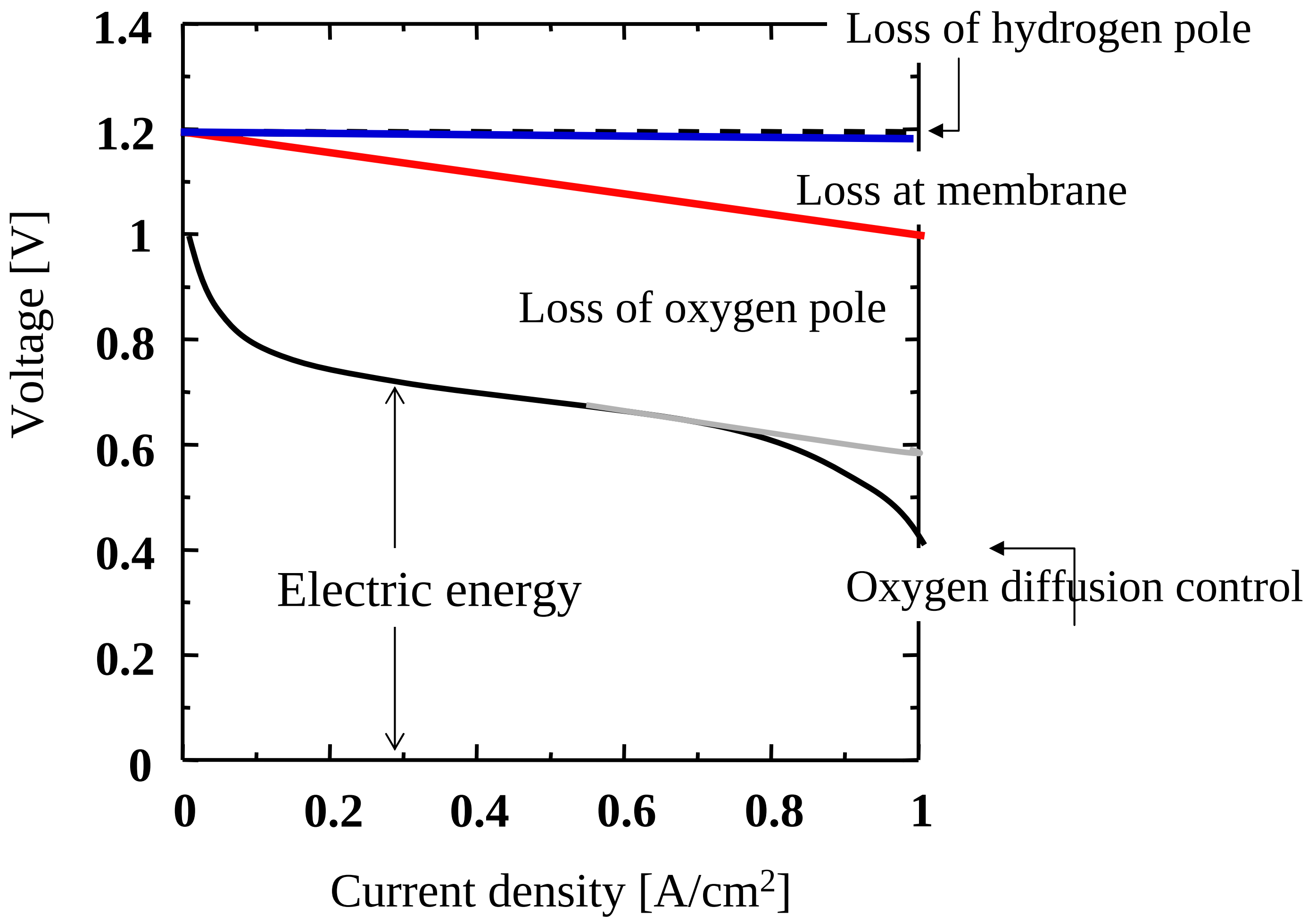
The True Nature of Internal Resistance Can be the Velocity of Diffusion and Reaction



Hydrogen pole Membrane Oxygen pole

Slow process gives a greater resistance. (Rate-limiting)

Internal Resistance Analysis



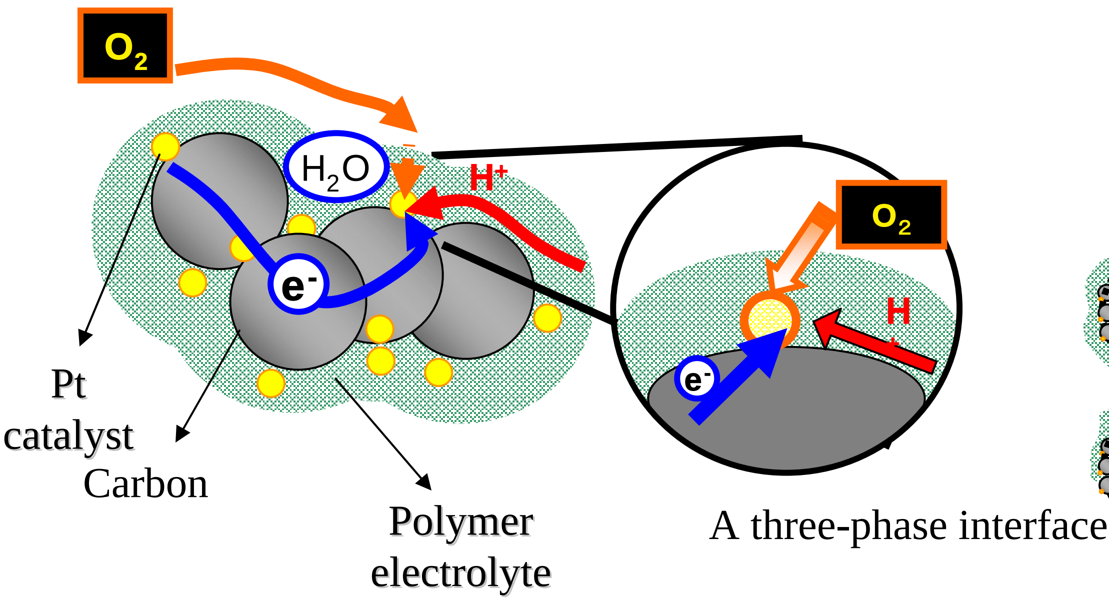
Urgent improvement is necessary for oxygen pole→membrane

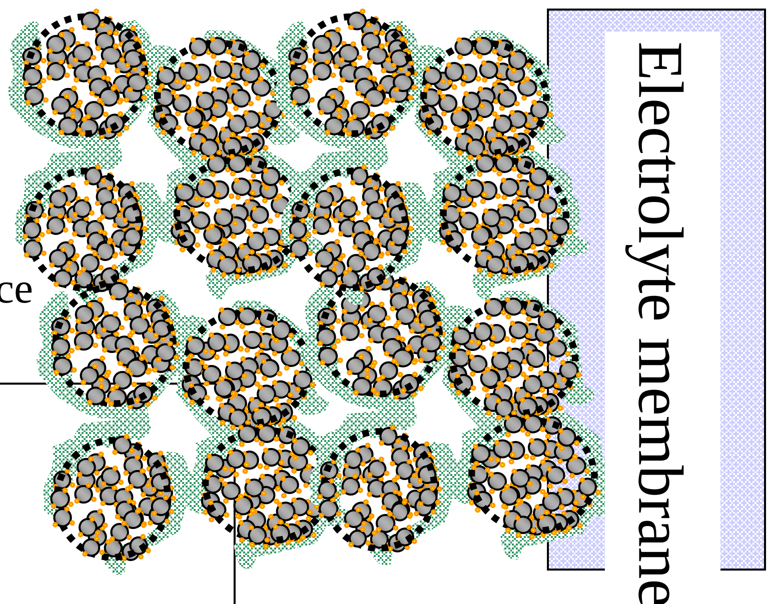
The Molecules, Ions, and Electrons are being Contacted with Platinum, Electrolyte, and Gas simultaneously,

Nano-level structure of catalytic layers

Carbon carrier produces agglutination so that polymer electrolyte cannot go in.

Platinum utilization factor is 20-30%.



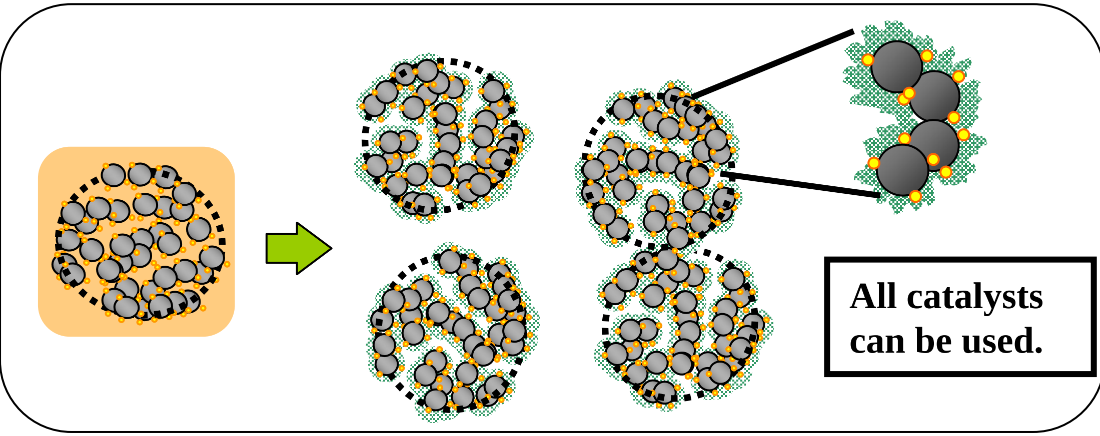


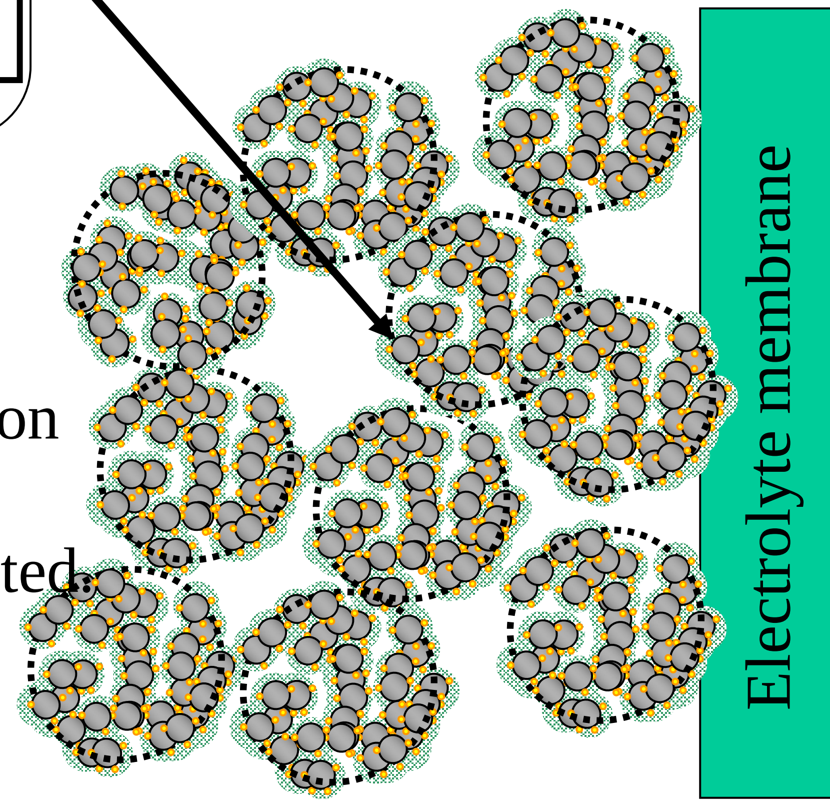
Nano-structural treatment is made to improve utilization rate at atomic level.

Size of carbon carrier: 30 nm

Pt catalyst particle size: 2 - 3 nm←almost 100% exposure.

Structure Control of Catalytic Layers by Nanotechnology



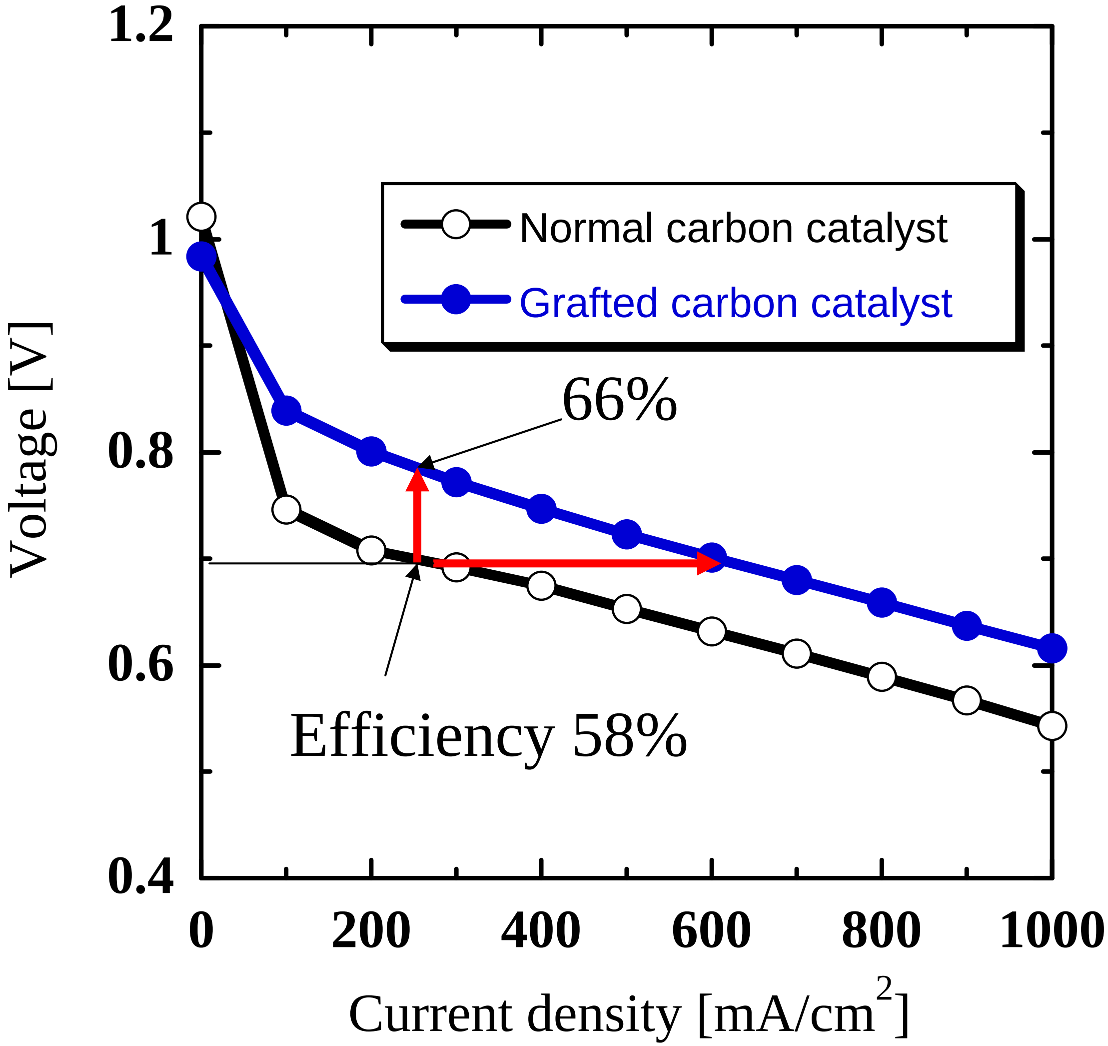


Monomer molecules, the ingredient of polymer electrolytes, are polymerized on carbon aggregate.

The surface of carbon should be activated.

Takeo Yamaguchi Laboratory, Department of Chemical System Engineering,
School of Engineering, The University of Tokyo

Improvement Should be Made for Efficiency and Capacity



There are some other causes as well.

Investigating the Rate-limiting for Oxygen Reduction Reactions

Oxygen reduction reaction on Pt surface

$$Pt + O_2 \longrightarrow Pt - O_2$$

$$Pt\text{-}O_2 + H^+ + e^- \underset{k_1}{\overset{k_1}{\rightleftarrows}} (O_2H)_{ads}$$

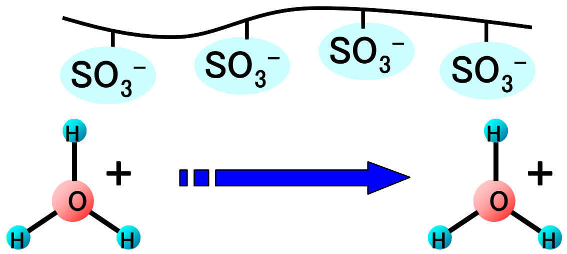
$$(O_2H)_{ads} + H_2O \underset{k_2'}{\overset{k_2}{\rightleftarrows}} 3(OH)_{ads}$$

$$(OH)_{ads} + H^+ + e^- \underset{k_3'}{\overset{k_3}{\rightleftarrows}} H_2O$$

The absorption at red light represents the rate-determining step.

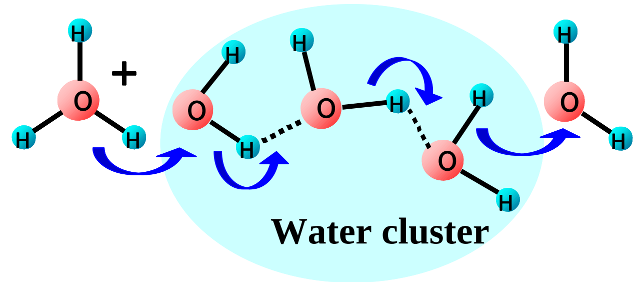
Proton Conductivity in Polymer Electrolytes

Vehicle mechanism

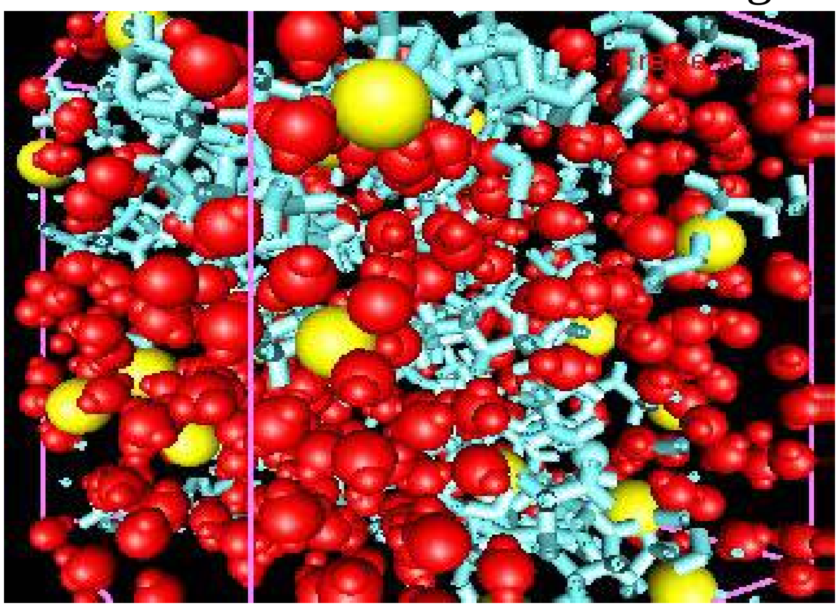


Free water becomes the transporter.

Grotthuss mechanism



Bound water around the sulfonic acid groups become the transporter.



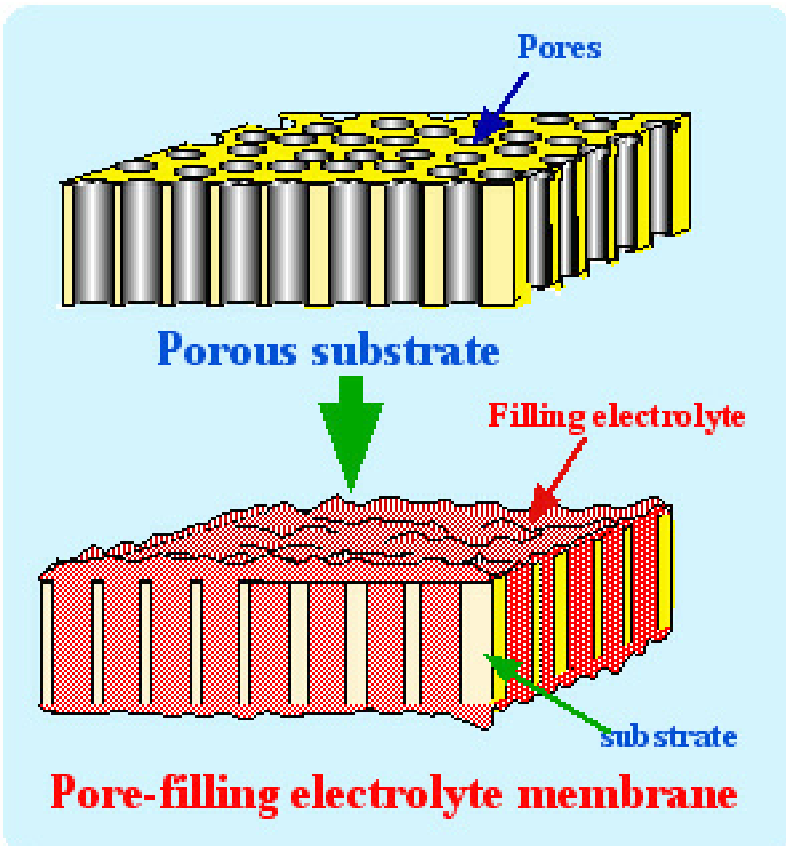
Red: water
Blue: polymer frame
Yellow: sulfonic acid group

•Water transforms itself into H_3O^+ to travel. (Vehicle mechanism)

•Hydrogen from water travels over to the hydrogen of other water. (Grotthuss mechanism)

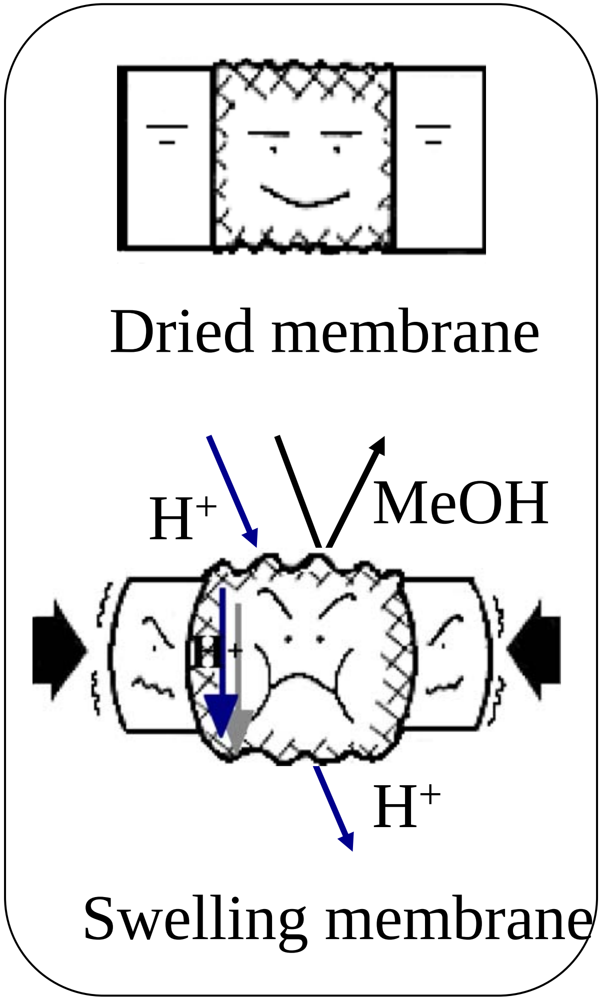
Images provided by Mitsubishi Electric Corp.

Filling the Electrolyte Membrane into a Nano-porous Membrane

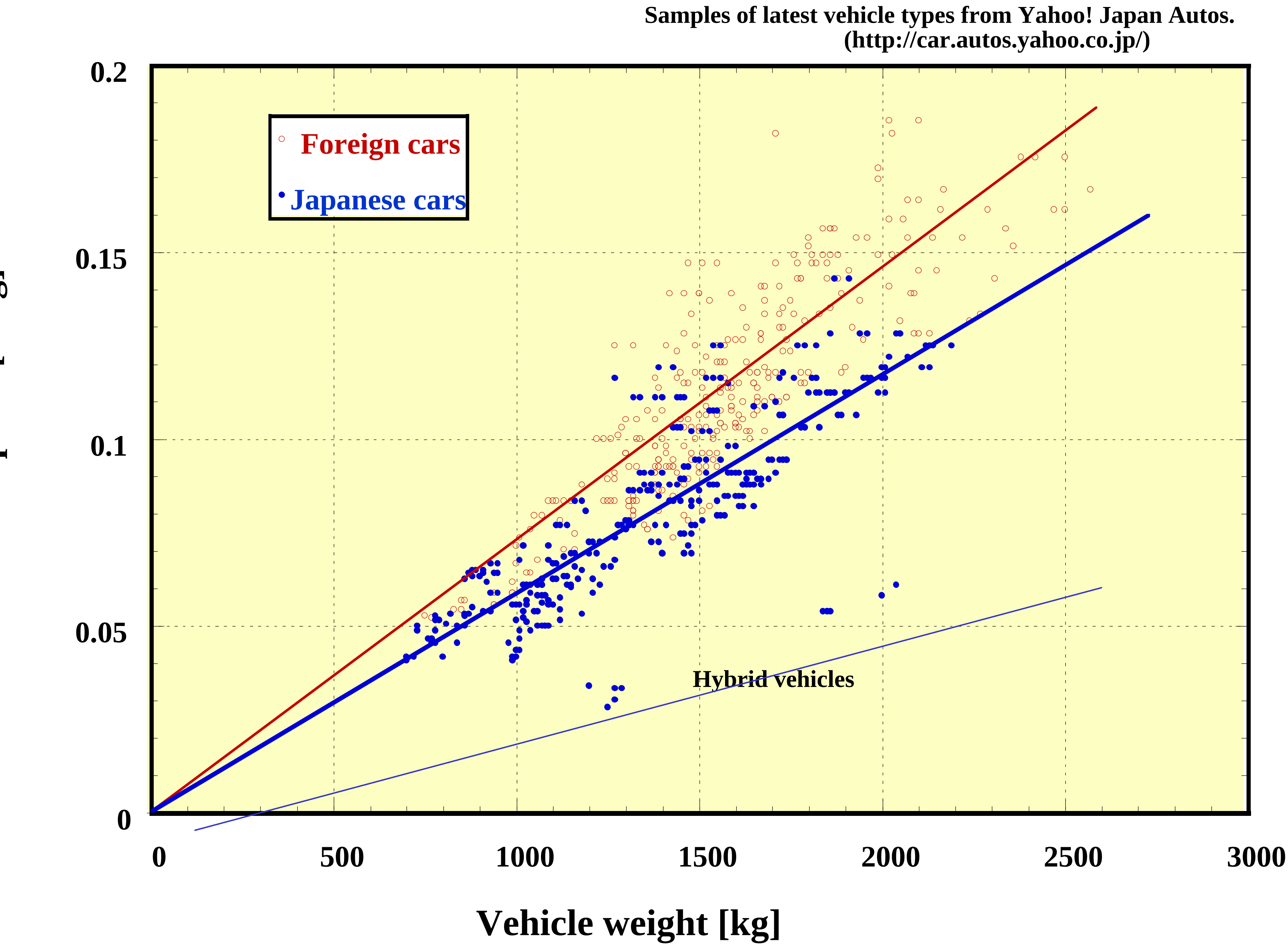


Polymer electrolytes are filled in the pores with the size of dozens of nm.
The micro-structure and water structure of the pore-filling polymer electrolytes are being controlled.

High proton conductivity is maintained while permeability of methanol is reduced to one millionth of the conventional membrane.



Takeo Yamaguchi Laboratory, Department of Chemical System Engineering, School of Engineering, The University of Tokyo


Samples of latest vehicle types from Yahoo! Japan Autos.
(http://car.autos.yahoo.co.jp/)
Foreign cars
Japanese cars
Hybrid vehicles
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
2500
3000
Vehicle weight [kg]

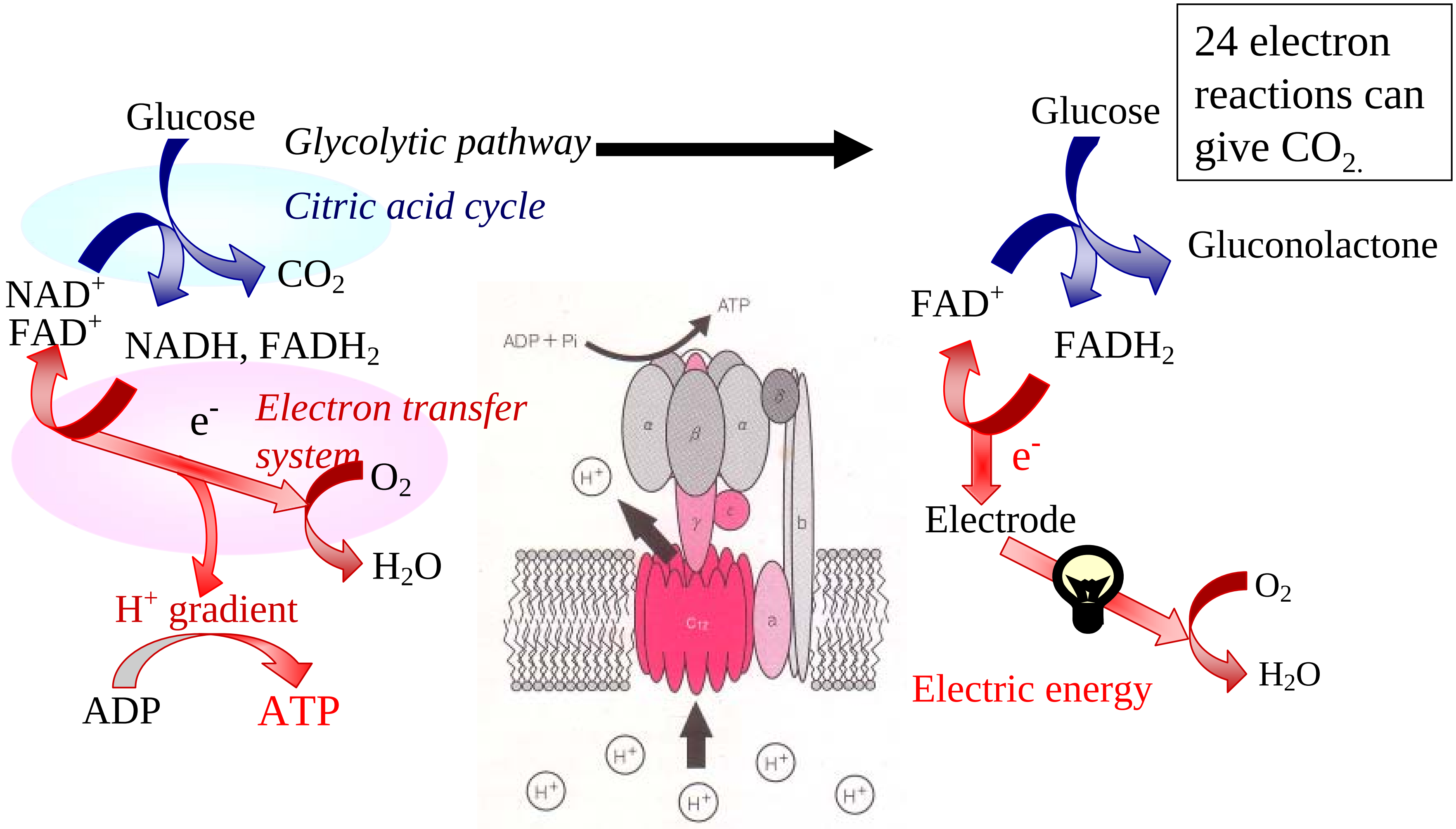
Energy Efficiency of Automobiles (Tank-to-wheel)

Current vehicles	13%	Unchanged
Limit of hybrids	35%	2.7 times
0.96V fuel cells	80%	6 times
Half weighted		12 times

Biofuel Cells

Organisms

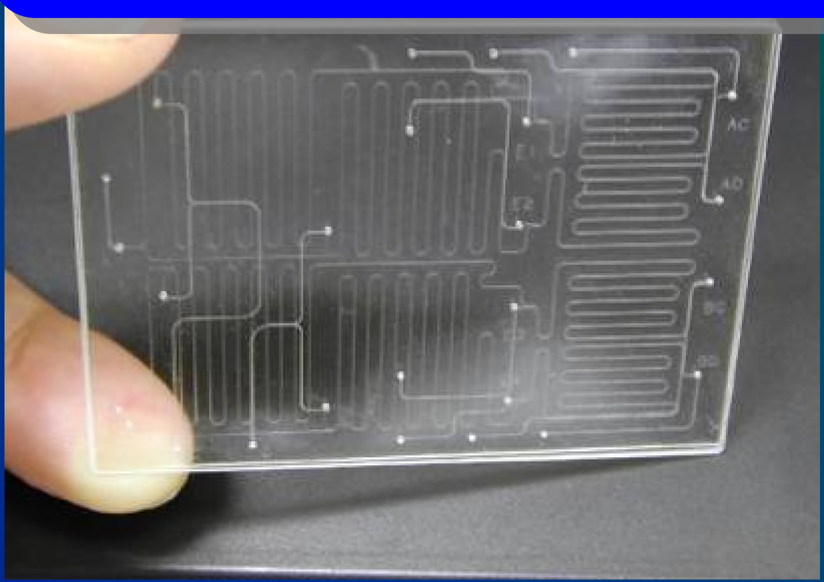
Biofuel cells



Micro/Nano Chemical System

Takehiko Kitamori Laboratory,
Department of Applied Chemistry,
School of Engineering,
The University of Tokyo

Examples of Micro-chemical Chips with Three-dimensional Structure



Advantages:

- High-function
- High-controllability
- High-designability

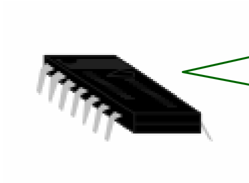
Independent technologies:

- Micro unit operation (MUO)
- Continuous-flow chemical process (CFCP)
- Thermal lens microscope (TLM)

Analogy of Electronics and Micro-chemical Chips

Electronics

Resistances, condensers, and diodes



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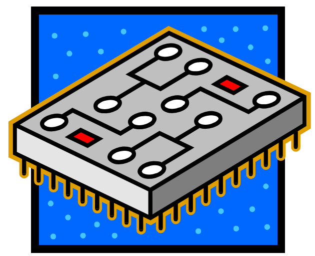
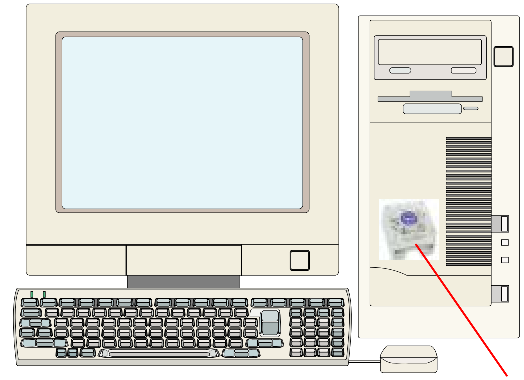
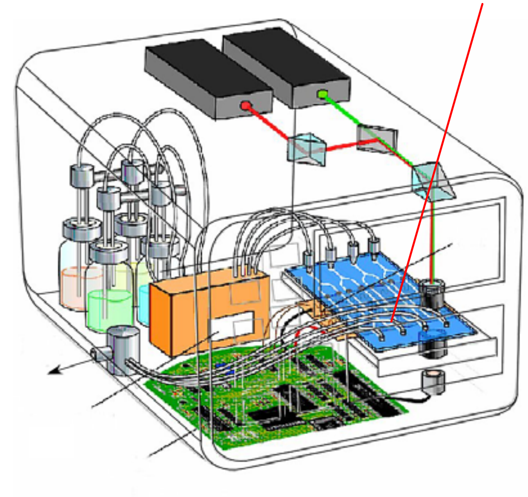




CPU

Microchemical chips

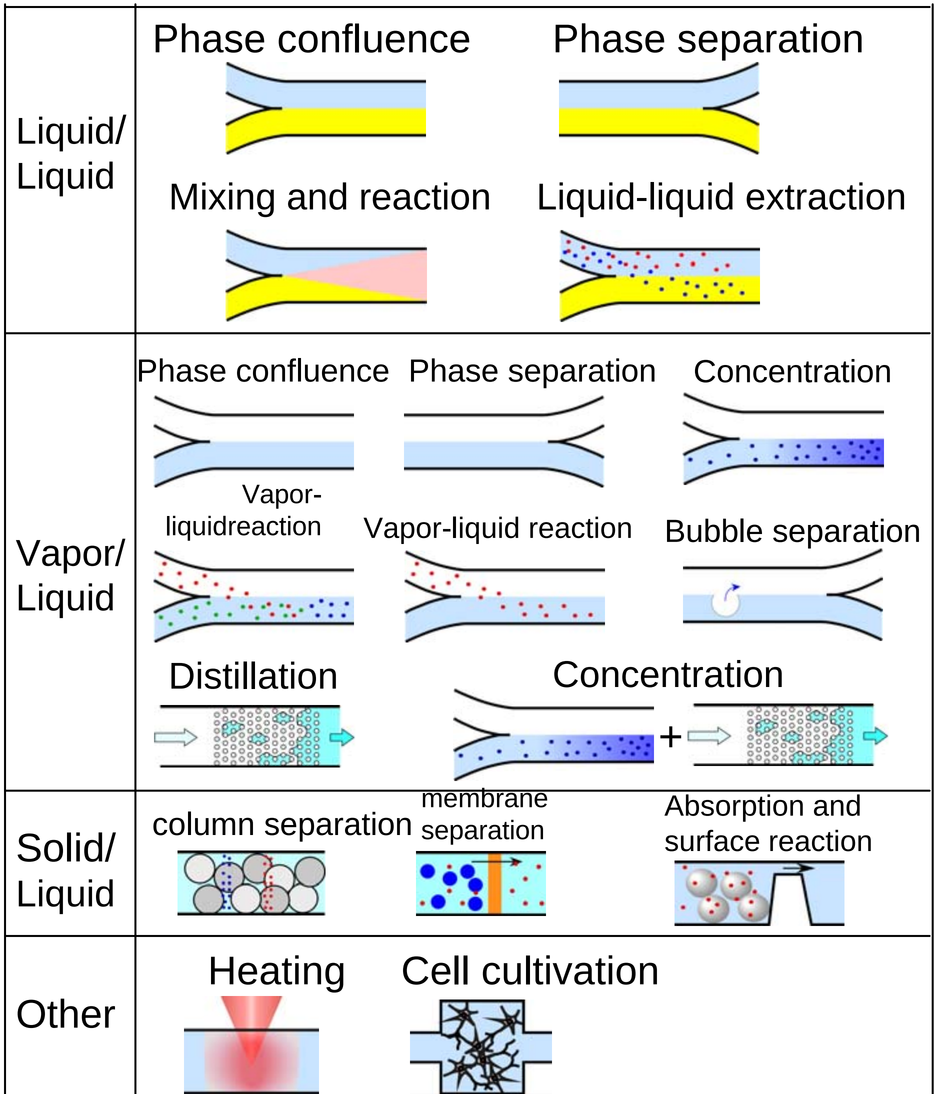
Reaction, extraction, purification, and distillation



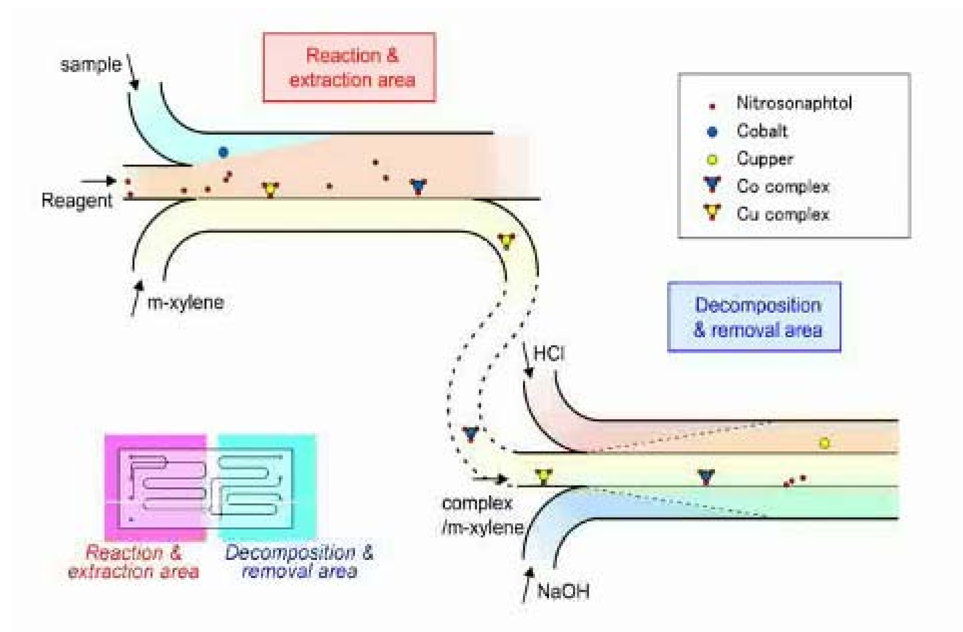
Integrated Component of Micro-chemical Chips and Chemical Unit Operation

Micro Unit Operation（MUO）＝Integrated Component

Continuous Flow Chemical Process（CFCP）＝Chemical Unit Operation

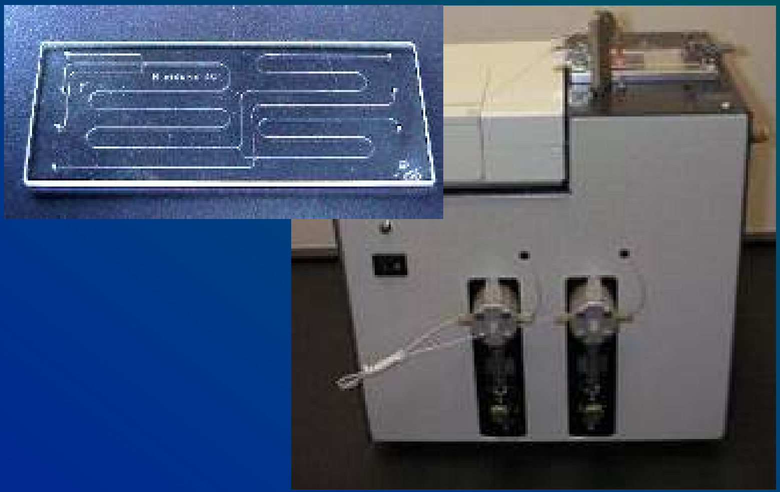


Free MUO Combination
by micro multiphase flow
＝Chemical Unit Operation



Chemical and Bio-Technology devices with micro chemical chip

μ-Extraction chip
Micro-environmental water analyzer



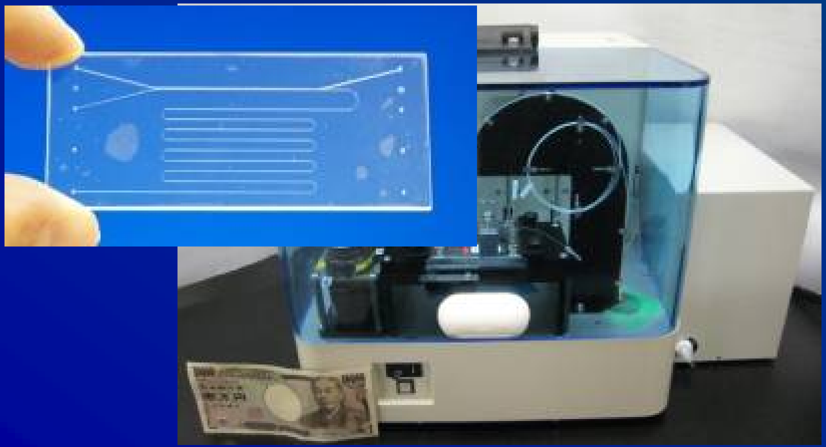
μ-ELISA chip
Microdiagnostics analyzer

Small

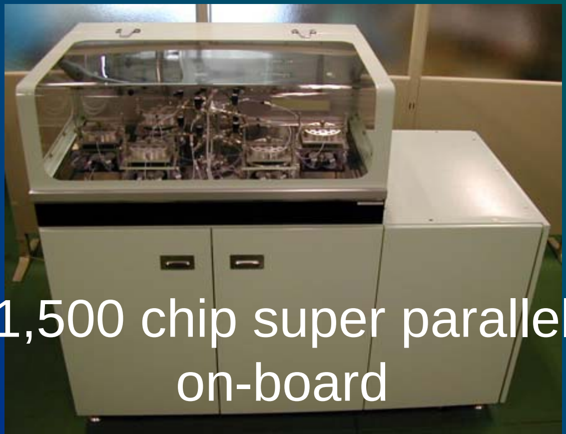
Quick

Easy

μ-Gas extraction chip
Clean room ammonia analyzer



Desktop chemical plant
(output of gel micro particles: 30t/year)

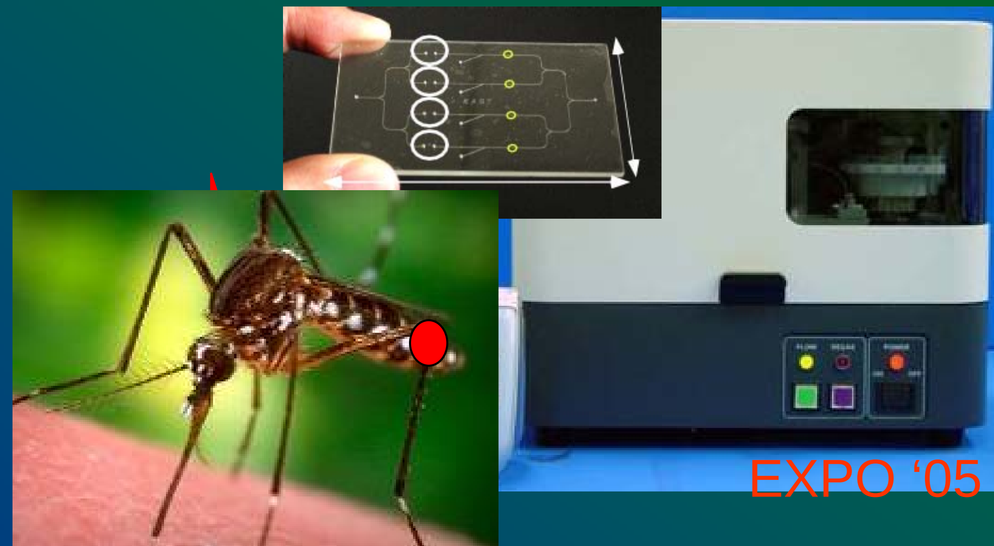


1,500 chip super parallel
on-board

Example 1: Microdiagnostics system
Cancer, Allergies, liver complaint, cardiac disease

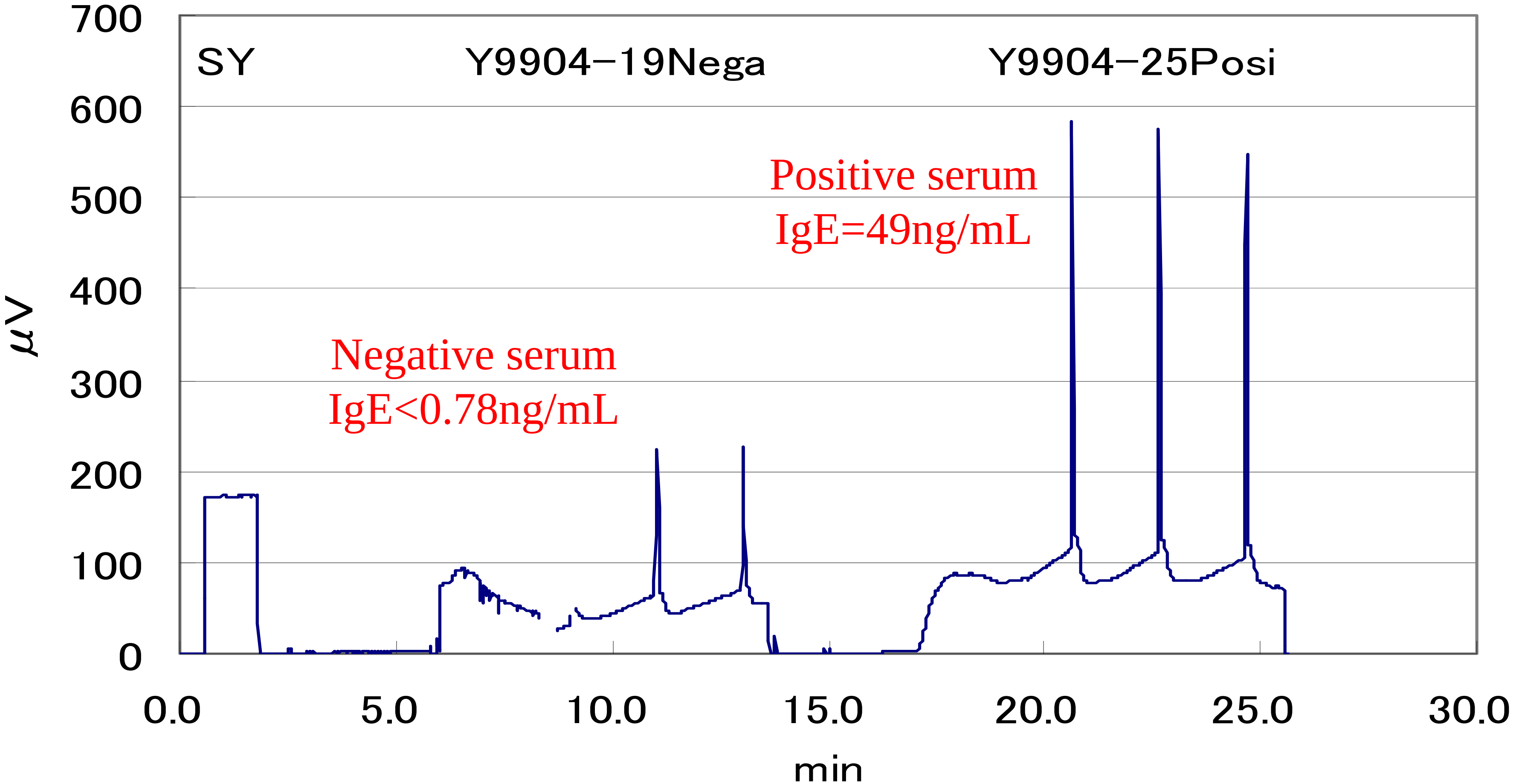
Conventional machine

Microchip machine



- Blood (Blood plasma) Volume : mL → μL indolence
- Analysis Time : day, hour → minute, second on site
- Operation : specialist → general
- Price : 10 million yen → less than 1 million
- User : large hospital, research company → individual personalization of exam

Express Diagnosis of Allergies
Detection of Specific Antibody for Hay Fever

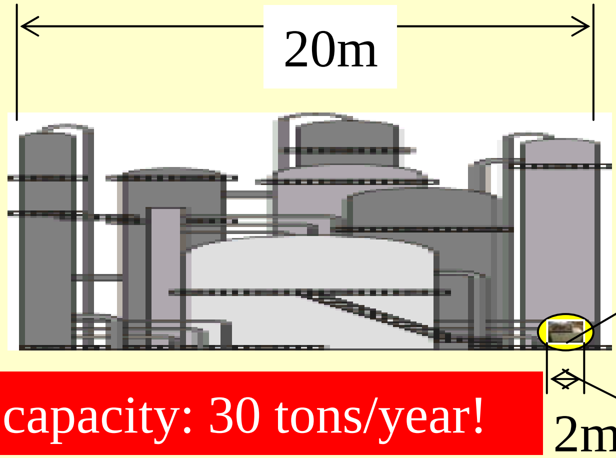


Conventional technology: over night

Micro-chemical chips: four minutes

Plants Made Into Chips

Chemical plant on desktop



Production capacity: 30 tons/year!

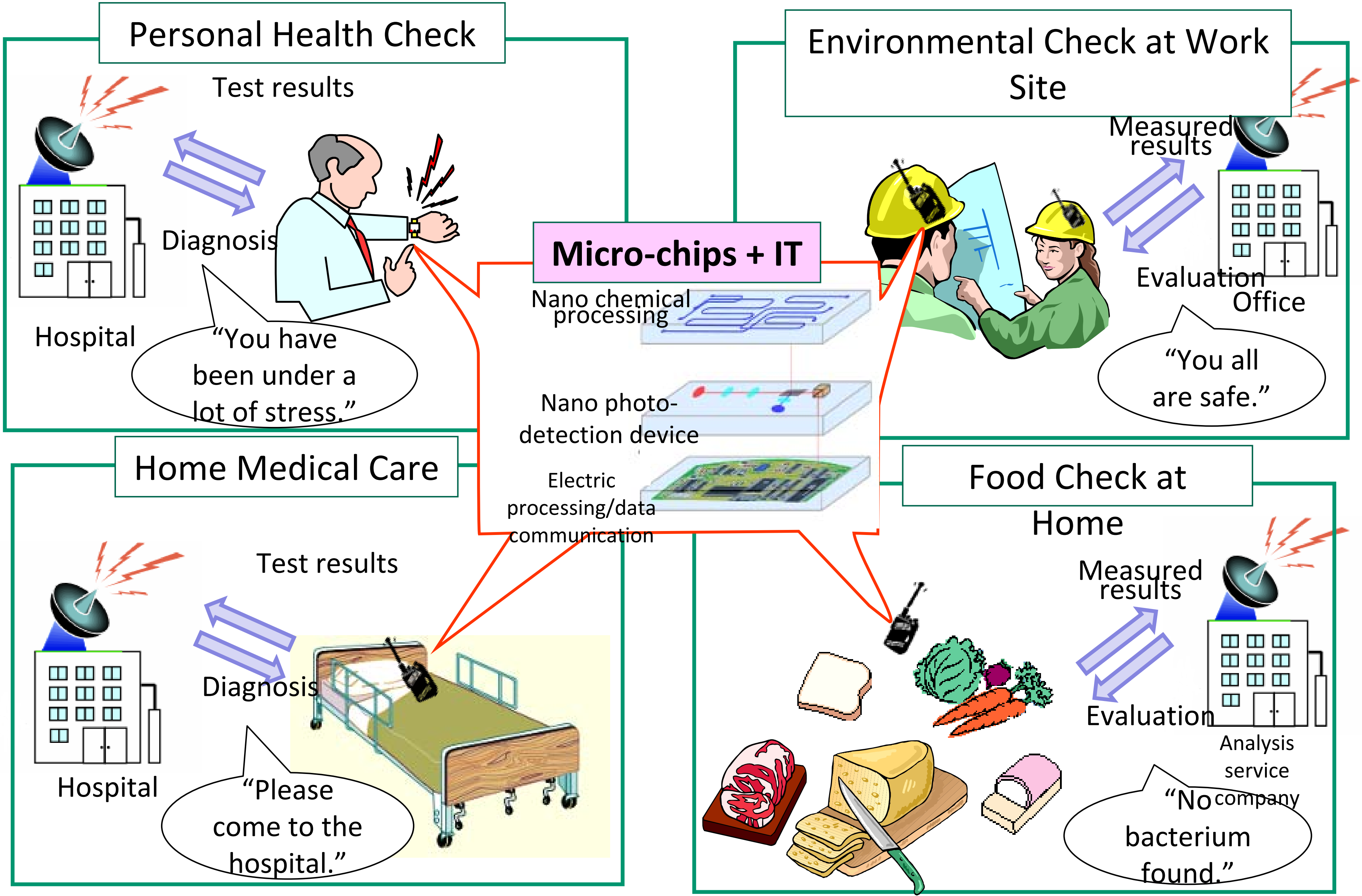
- Space saving
- Energy-conserving
- Cost reduction

Anticancer drug production plant
Toxic and explosive

10kg/ month → Enough for medical supply production

- Risk reduction
- On-demand operation

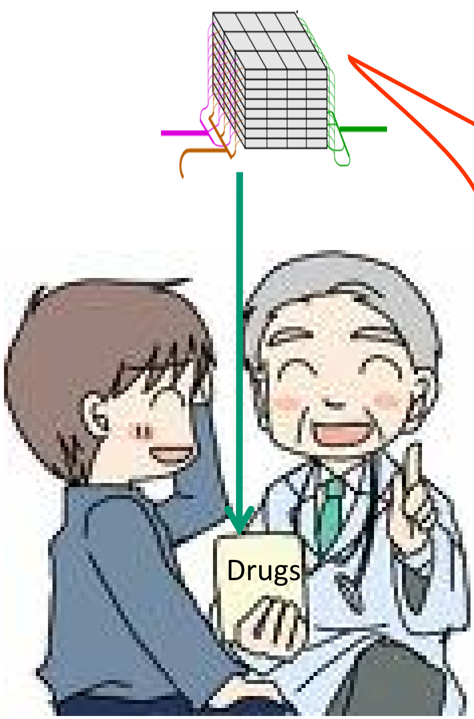
Contributions to a Secure and Safe Society
Through Networking of Analytic and Diagnostic Functions Using Devices



Contributions to Chemical Synthesis/Drug Production and Resource/Energy Issues

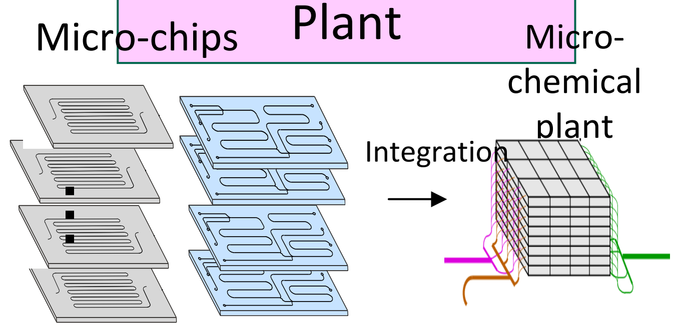
Chemical Synthesis/Drug Production

In-hospital drug synthesis plant

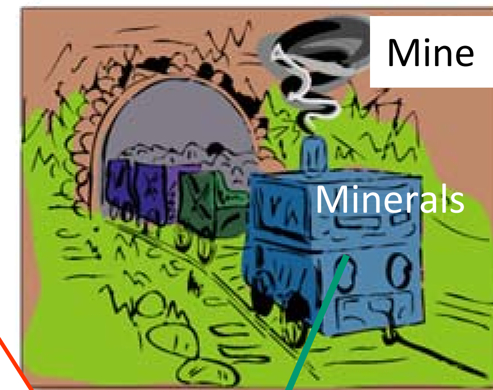


Coordination of short-lived radioactive diagnostic agent issues: Tailor-made medicine

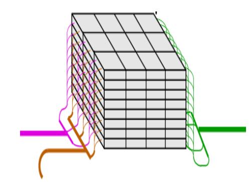
Micro-chemical Plant



Natural Resources/Energy



Solvent Extraction Plant



To collect precious natural resources with low energy (e.g., uranium, rare metals)

Essential Science and Technology

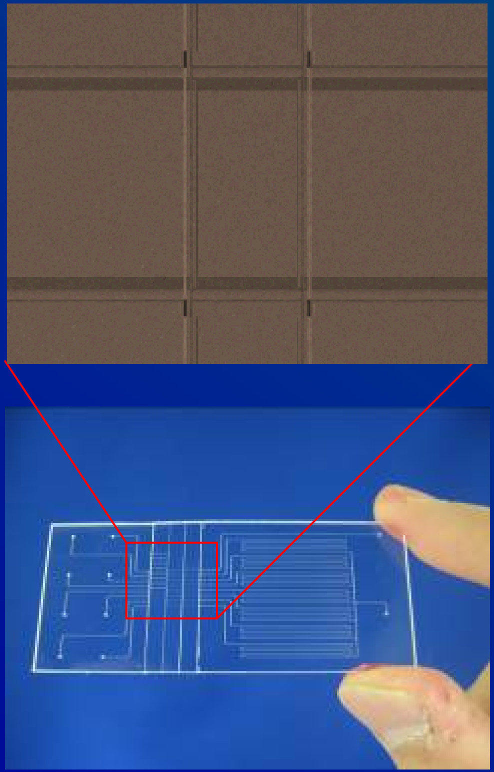
Processing	1) Micro/nano processing
Fluid control	2) Micro fluid control
	3) Micro fluid control devices
Interface	4) Surface modification
	5) Interfacial fluid control
Detection	6) Ultra-sensitive detection
Process	7) Chemical reaction control
	8) Chemical process control
System	9) System designing and control
Science	10) Micro/nano fluid, chemistry, and biochemistry

Most powerful

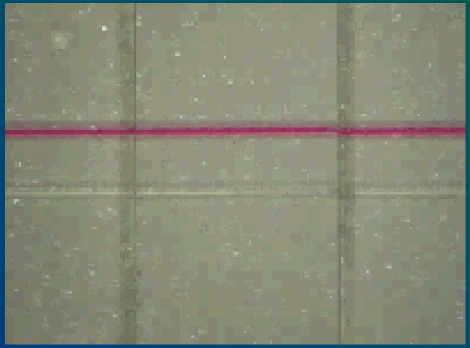
New academic field and highly intensive technology of science and engineering

Microvalve
Create Your Own for What You Are Missing

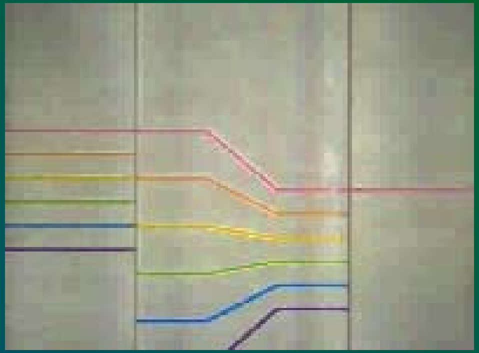
Base structure



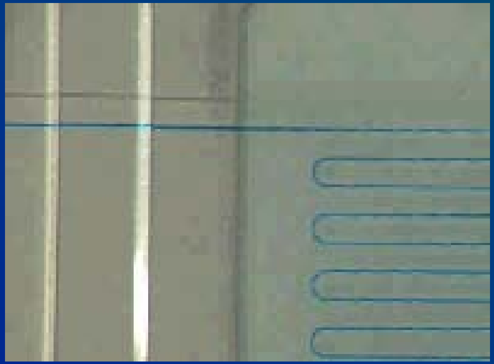
Nano injector



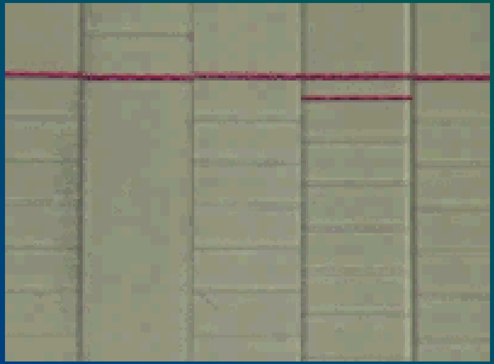
Switching



Introduction of vapor

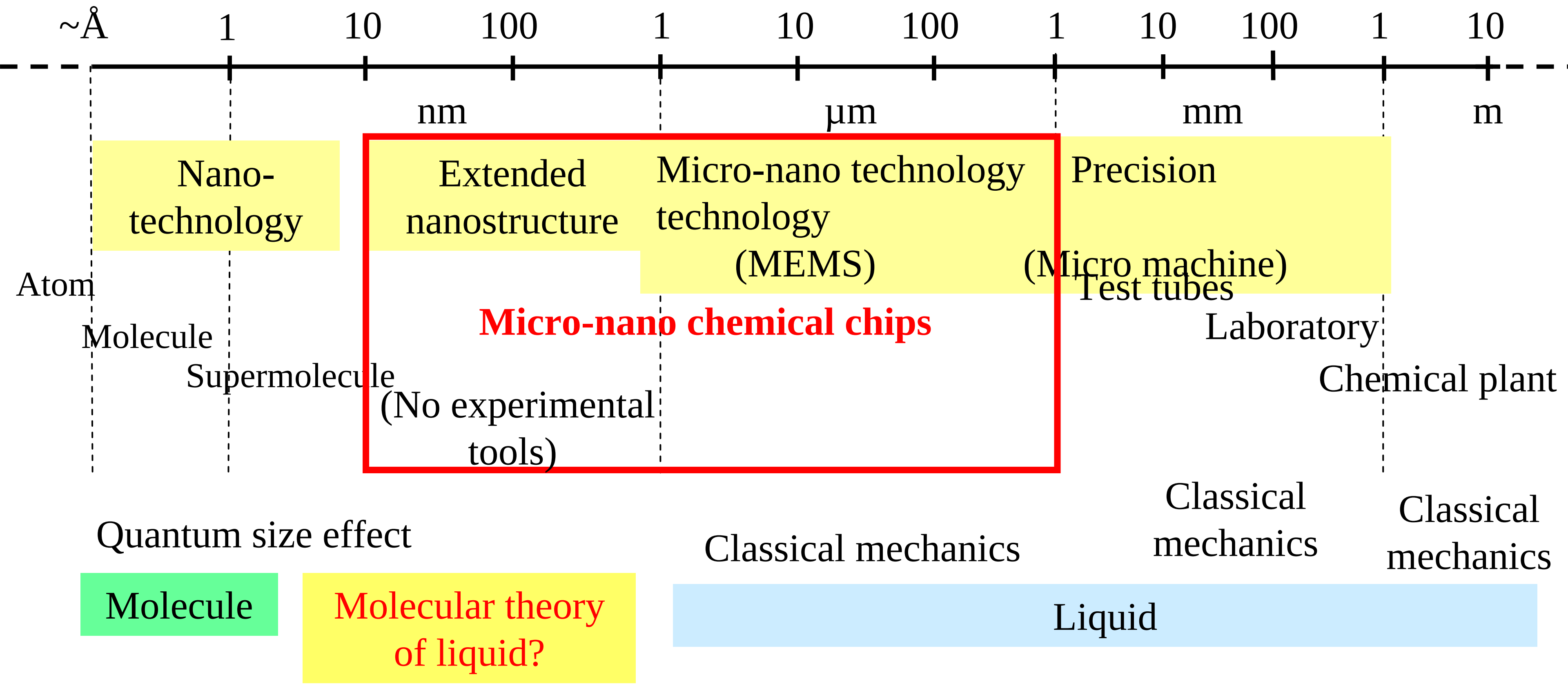


Dispenser



Examples of different types of valves

Size Hierarchy and Micro-nano Chemical Chips



Characteristics of extended nanostructure:

Nano-fluid properties ▪

Liquid structure of nano-space ▪

Reactions in nano-space ▪

No conventional knowledge has been developed yet.

Characteristics of micro-space:

▪ Small materials with extremely short energy diffusion distance

▪ Gravity << interfacial tension

▪ Laminar flow

Conventional knowledge has gone too far and has become absurd.

Two-phase Flow in Micro-channel
ー Streamline Tracing ー

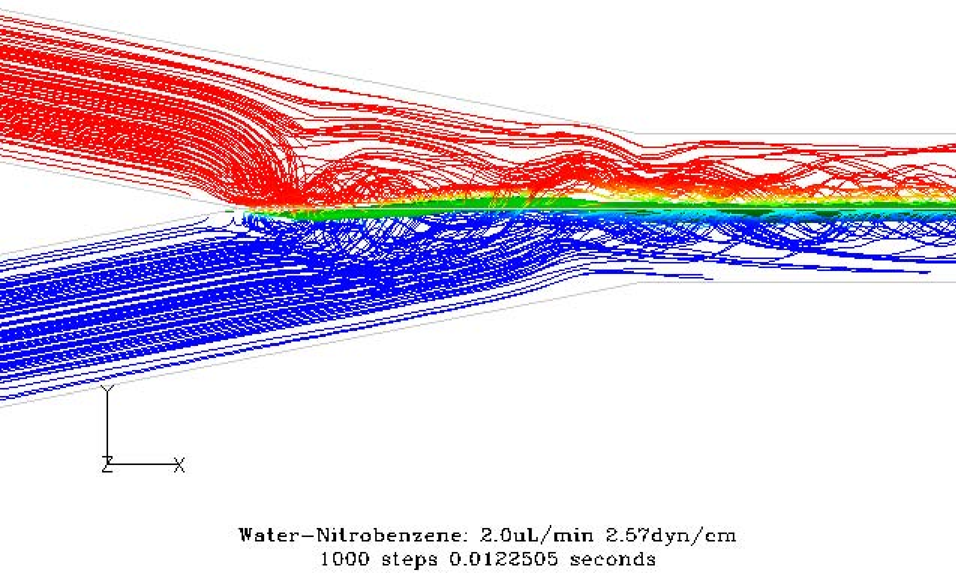
Ordinary system

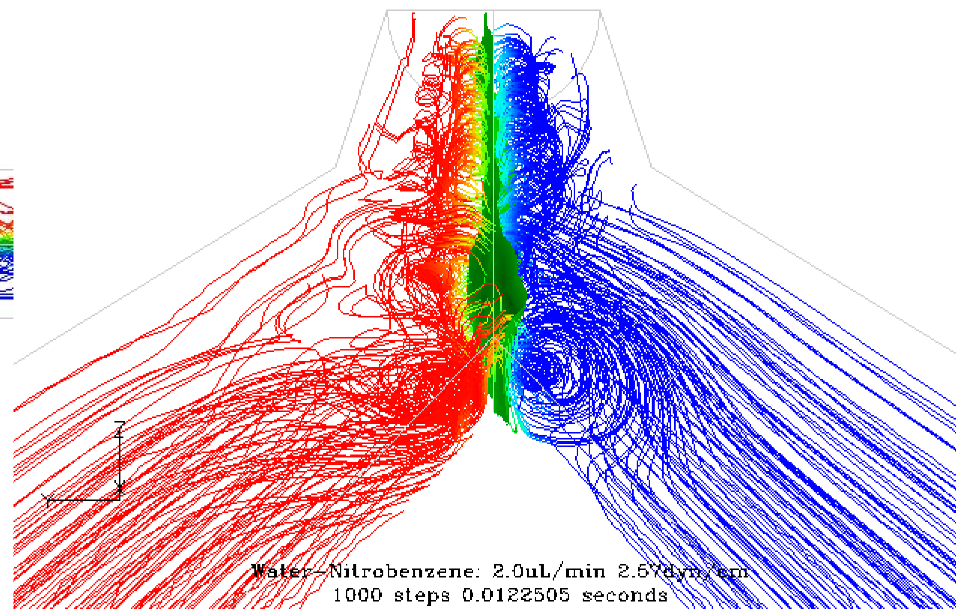
・Gravity does no work but instead, interfacial tension governs the flow → aligned both left and right

・Reynolds number can be 5 at its best → laminar flow

・The interface of laminar flow is stirred → it appears as turbulent flow (extraordinary)

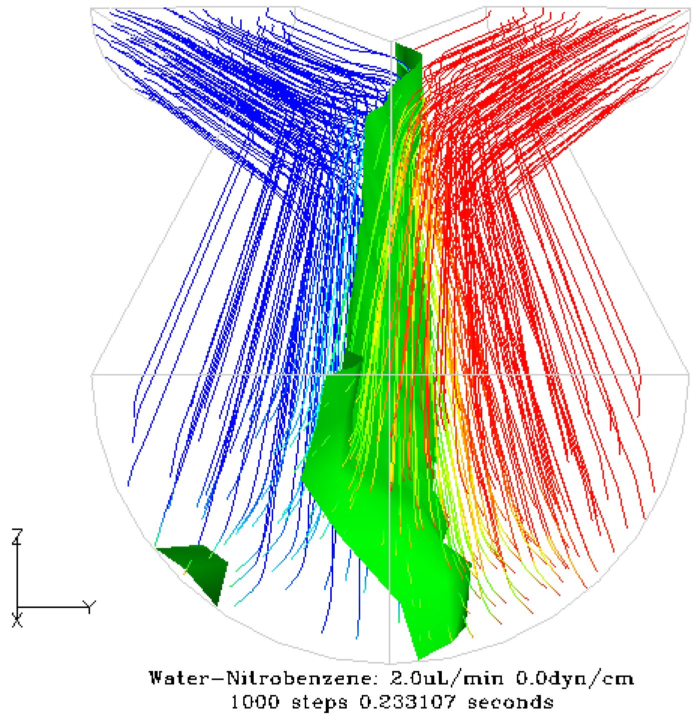
It appears as laminar flow from one side while it appears as a turbulent flow on the whole.

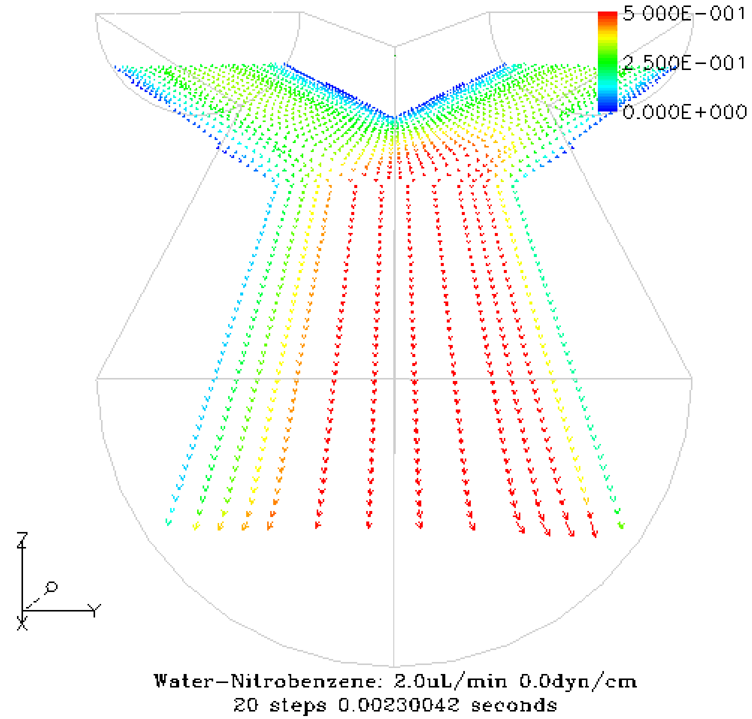




Three-dimensional Simulation of Micro-two-phase Flow

There is no turbulence but only laminar flows by macroscopic observation.





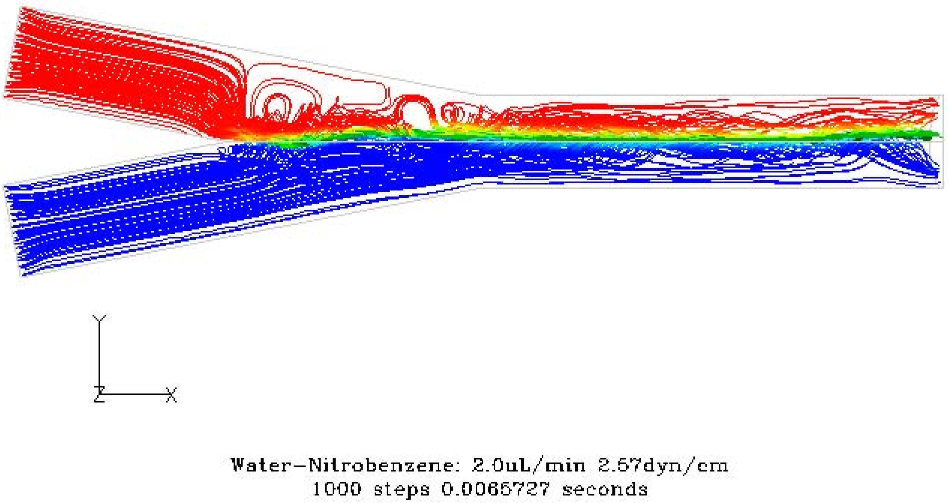
Three-dimensional Simulation of Micro-two-phase Flow

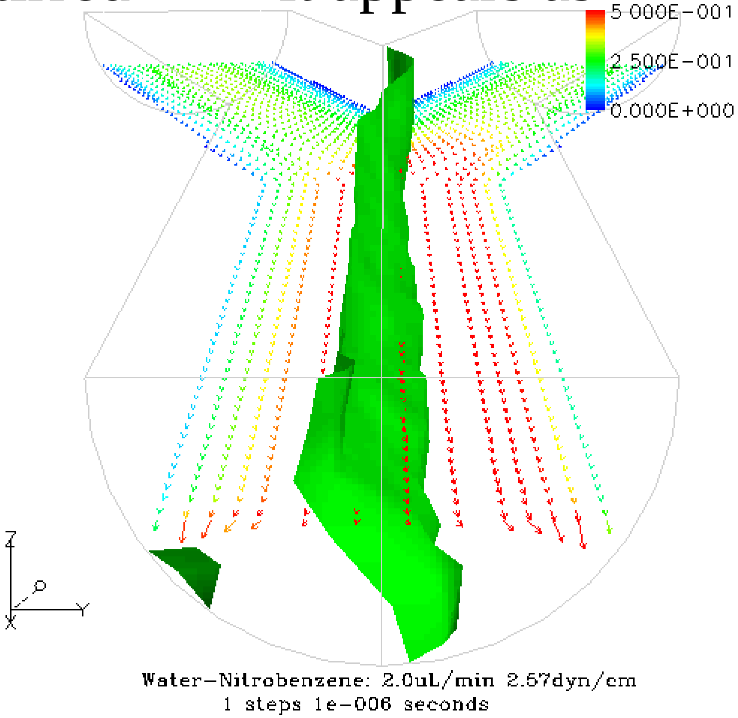
Ordinary system

・Gravity does no work but instead, interfacial tension governs the flow → aligned both left and right

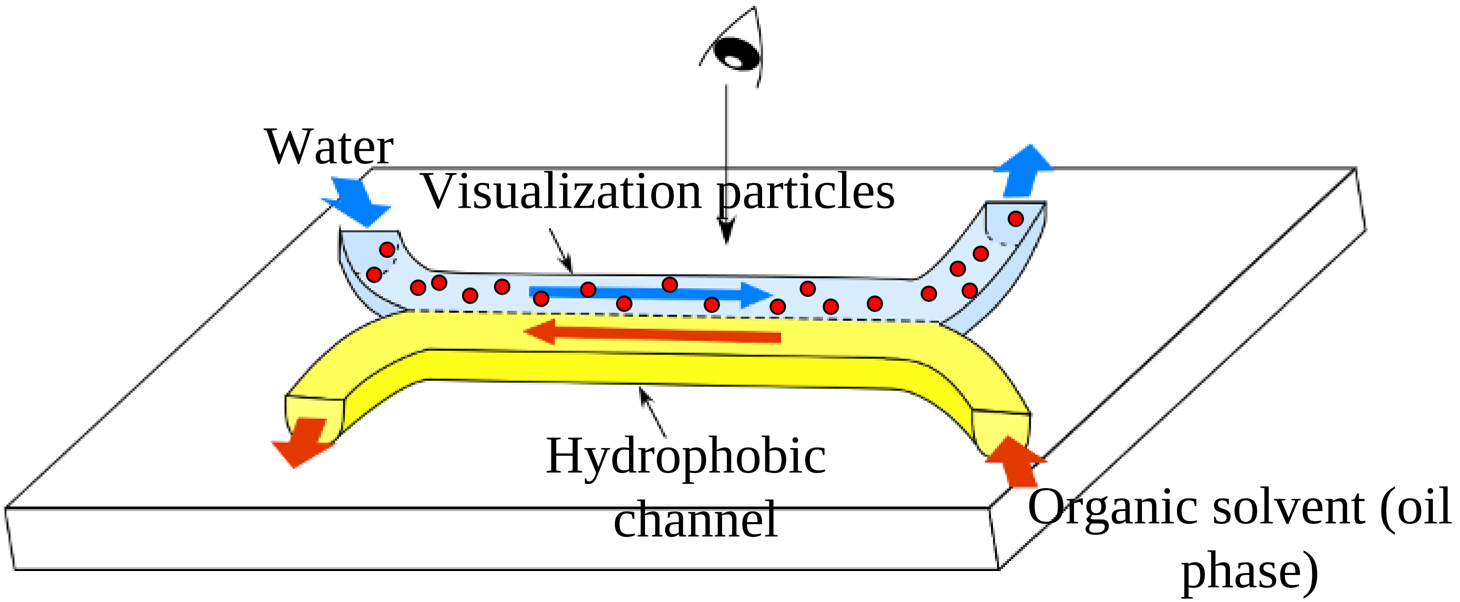
・Reynolds number can be 5 at its best → laminar flow

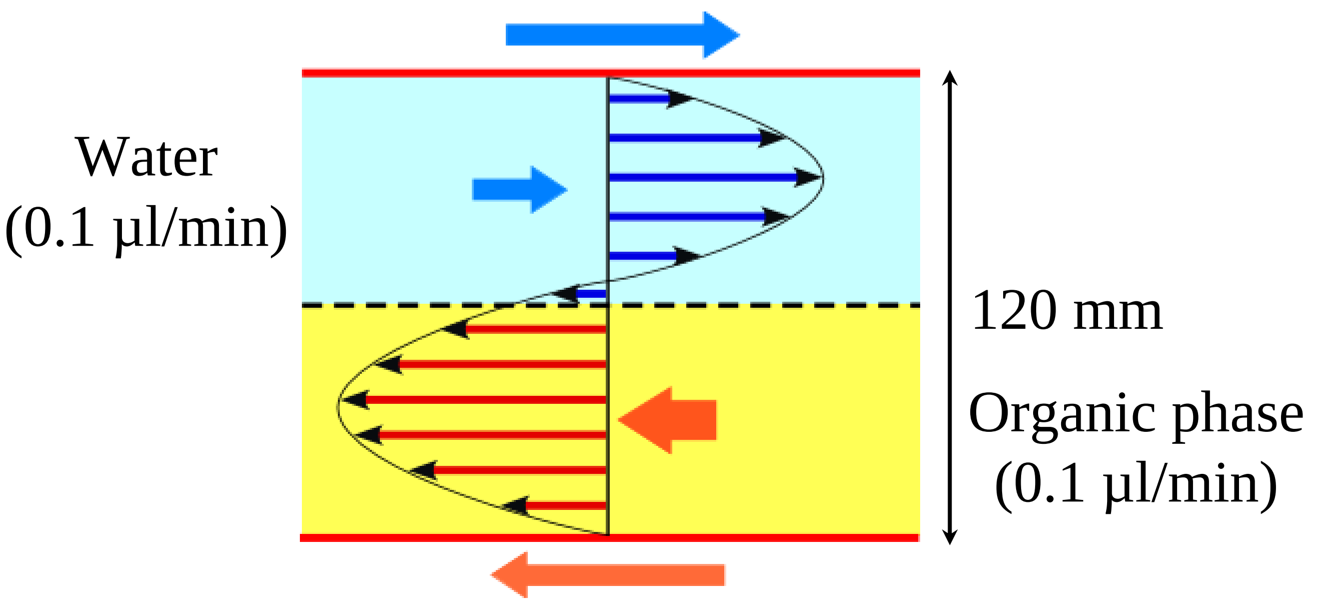
・The interface of laminar flow is stirred → it appears as turbulent flow (extraordinary)



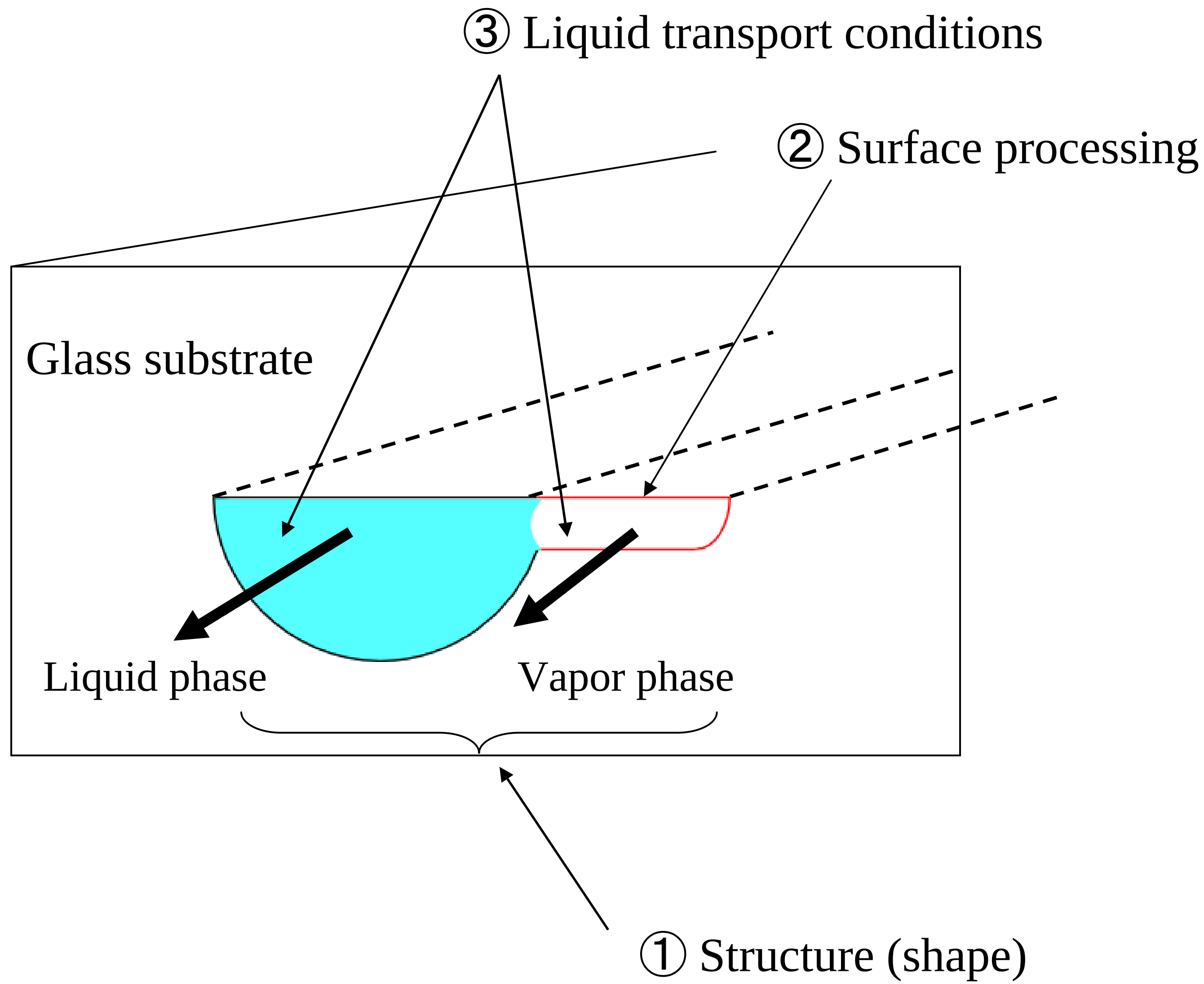


Water and Oil Counter-flow

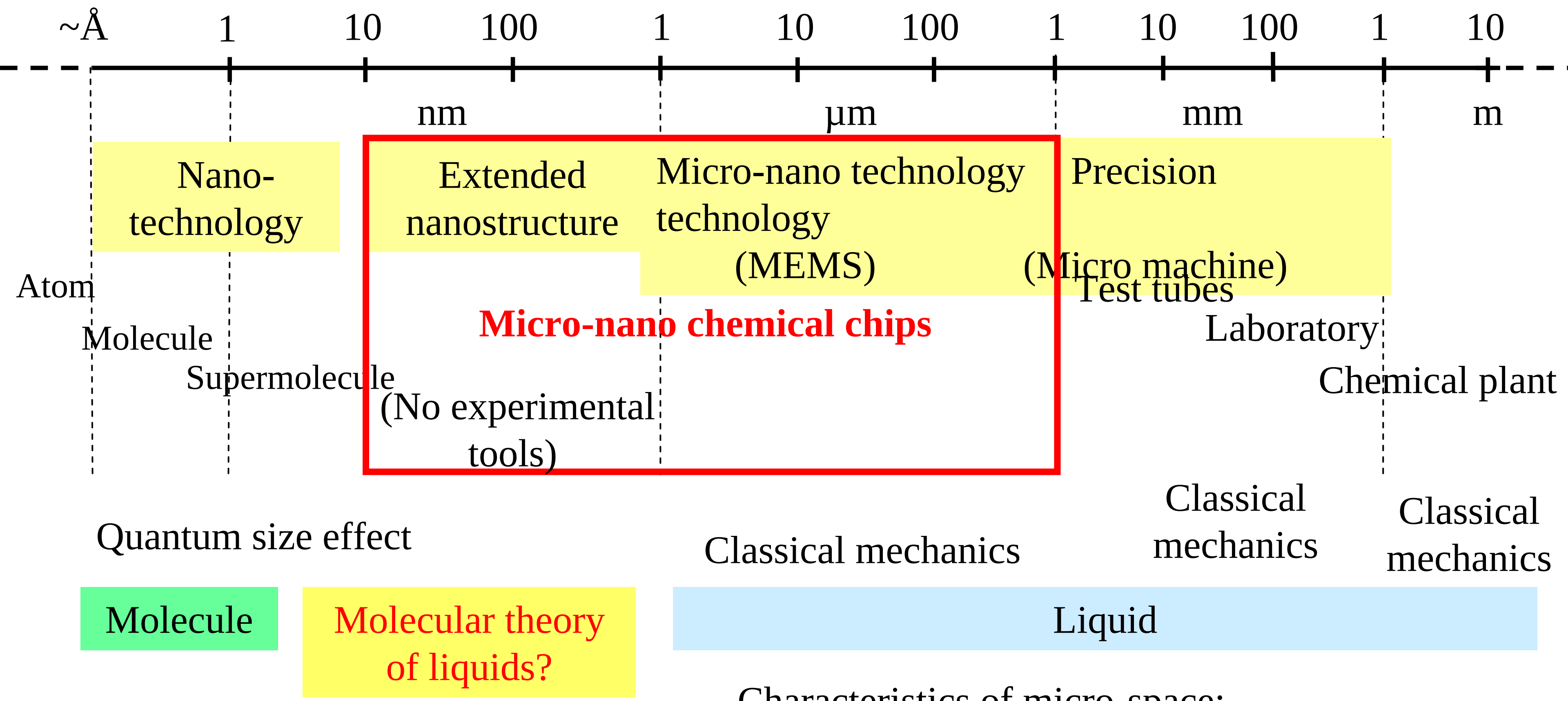




Parallel Flow Implementation of Vapor Phase and Liquid Phase (Three Conditions)



Size Hierarchy and Micro-nano Chemical Chips



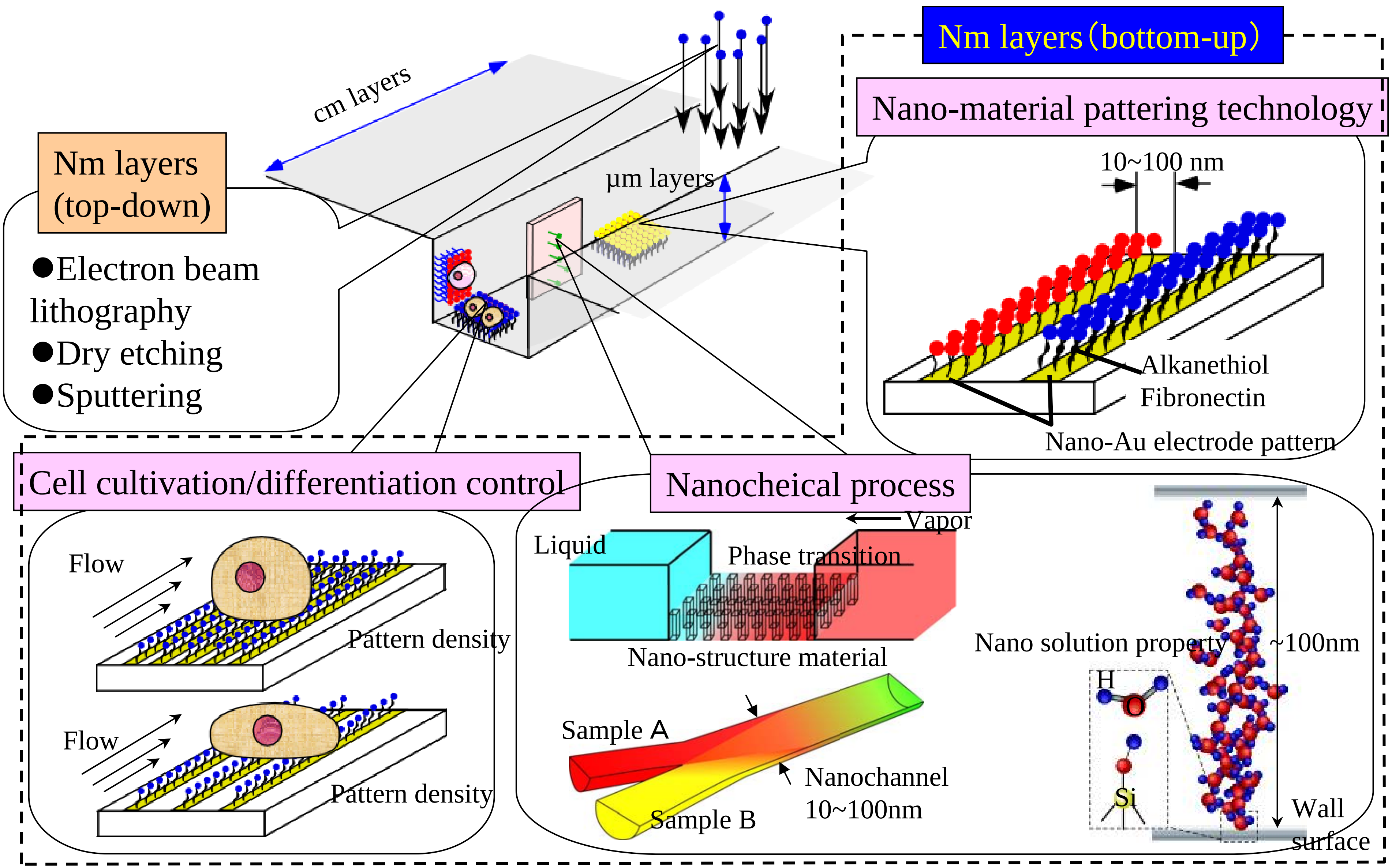
Characteristics of the extended nanostructure:
- Nano-fluid properties
- Liquid structure of nano-space
- Reactions in nano-space

No conventional knowledge has been developed yet.

Characteristics of micro-space:
- Small materials with extremely short energy diffusion distance
- Gravity << interfacial tension
- Laminar flow

The conventional knowledge has gone too far and has become absurd.

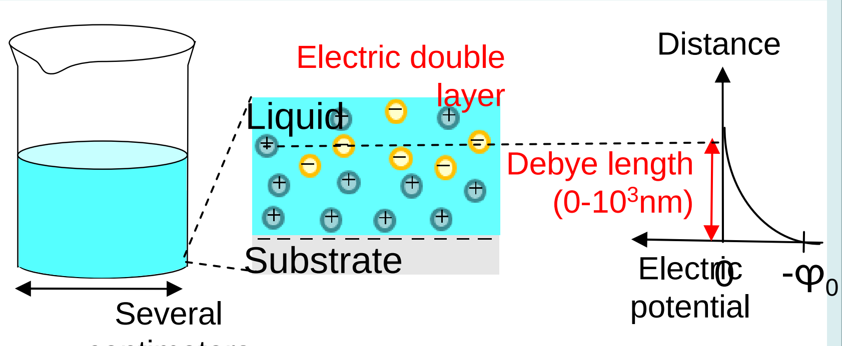
Nano-in-Micro Structuring and Research Mission



Academic Positioning of Extended Nano-space Fluidics

Studies in Chemistry and Mechanical Engineering

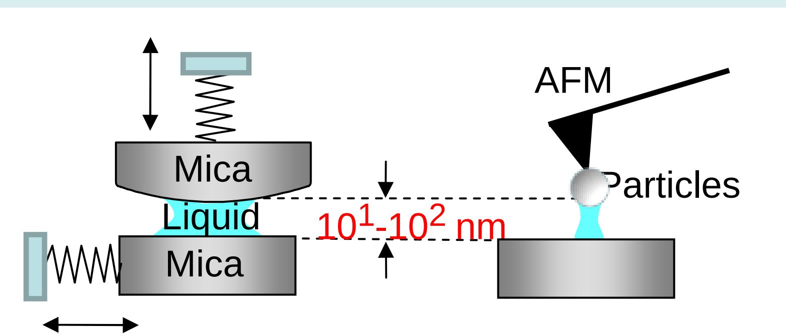
(1) Chemical thermodynamics near the surface



Over 500 cases reported since 1960.

Open space (bulk liquid and equilibrium)

(2) Mechanical Engineering in nano-space (Tribology)



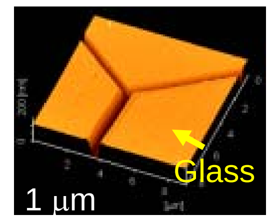
Over 200 cases reported since 1980.

Static fluid and dynamic chemical probe reaction were excluded as it is difficult to operate chemically.

Approach from Extended Nano-fluidics

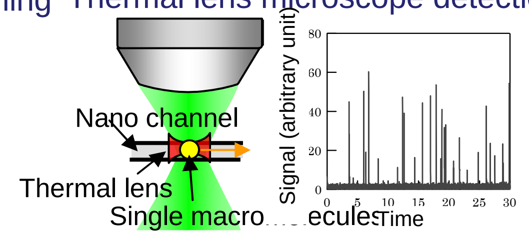
Development of Basic Experimental Tools (to make/measure/lead)

Nano-engineering/joining



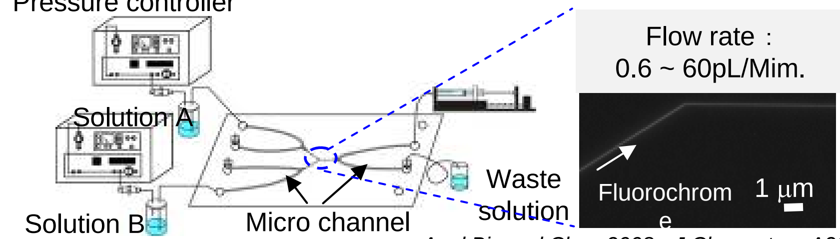
Anal.Chem.2002 *Angew.Chem.Int.Ed 2007*

Thermal lens microscope detection



Anal.Sci.2008 *μTAS2007*

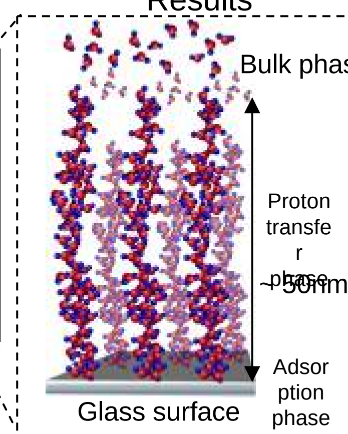
Pressure-driven fluid control



Anal.Bioanal.Chem2008 *J.Chromatogr.A2006*

Experimental Results

February 2007 number



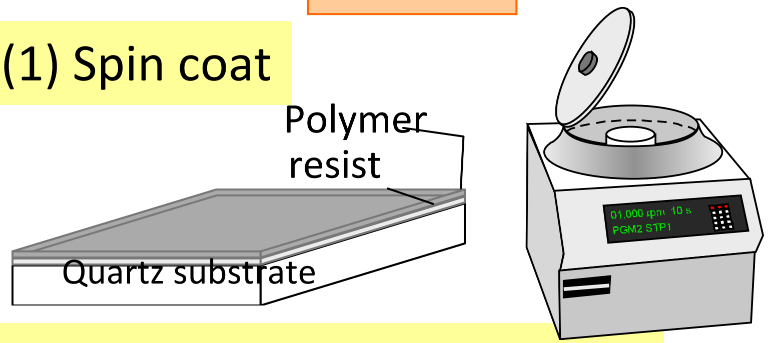
Effects/Phenomena Detected

- Water molecule ordering *Angew.Chem.Int.Ed 2007*
- Increased viscosity (4 times) *Anal.Chem.2002*
- Decreased permittivity (1/7 times) *Anal.Chem.2002*
- Change in chemical reactions *Anal.Bioanal.Chem2008*
- Increased proton transfer rate (20 times, NMR measurement) *Angew.Chem.Int.Ed 2007*

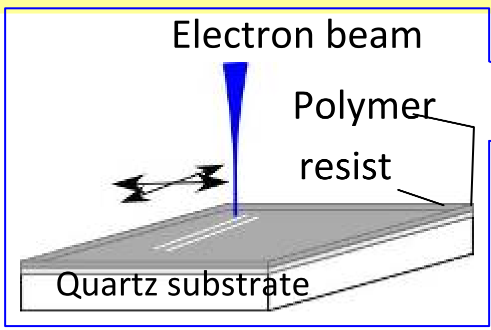
Process and Results of Extended Nano-space Processing

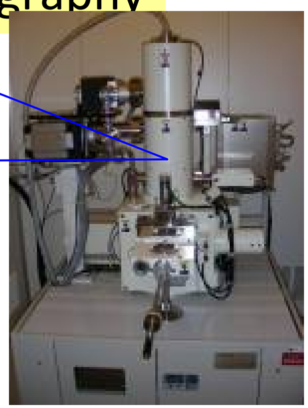
Process

(1) Spin coat

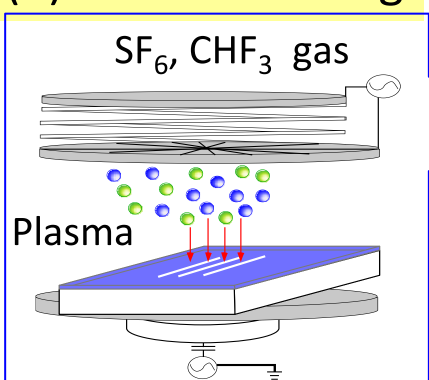


(2) Electron beam lithography



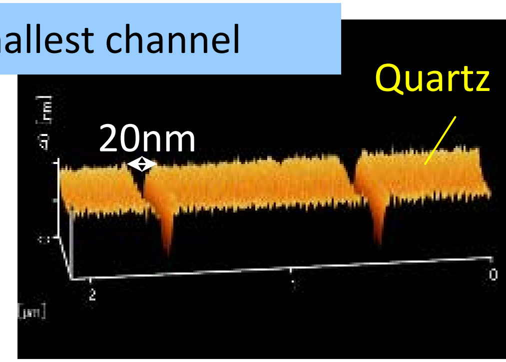


(3) Plasma etching



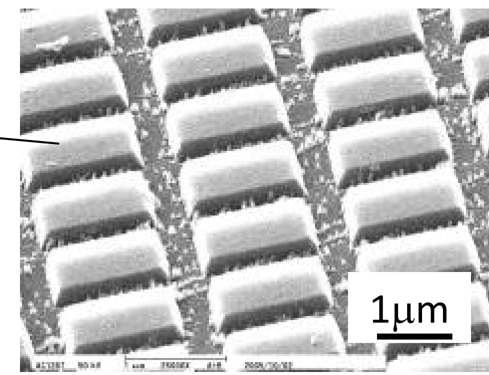
Results

The world smallest channel

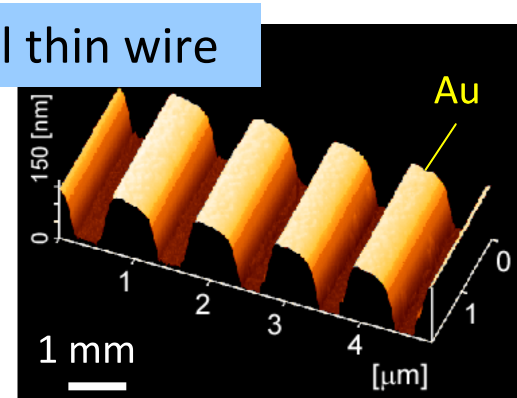


Nano-pillar

Quartz



Nano metal thin wire



Extended Nano-space Science and Engineering and Creation of New Functional Devices

Extended Nano-space Science and Engineering

Technology Innovation

1. Extended nano-space processing
2. Measurements and analyses in nano-space
3. Nano fluid control
4. Nano structure system control
5. Nano surface control

System Innovation

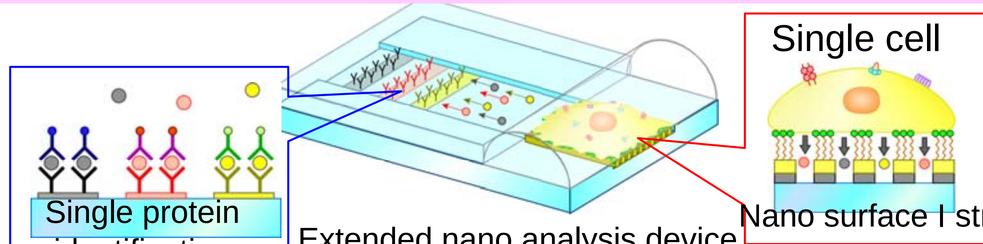
1. System control
2. System integration
3. Macro/Micro interface
4. Mechanochemical interface

Science Innovation

1. Extended nano structural dynamics
2. Extended nano fluid dynamics
3. Extended nano space chemistry
4. Extended nano space cell science

Creation of New Functional

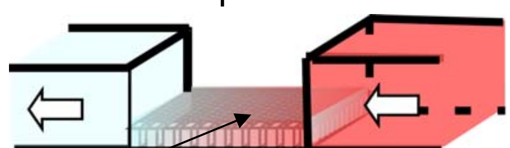
Single Cell/Single Molecule Proteomics (A key to the next generation biotechnology)

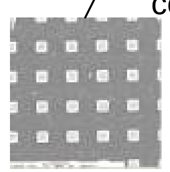


Microscopic Energy Device (Generation and Supply of Dispersion Energy)

Extended nano heat pipe

Ultra fine cooling device for the next generation chips

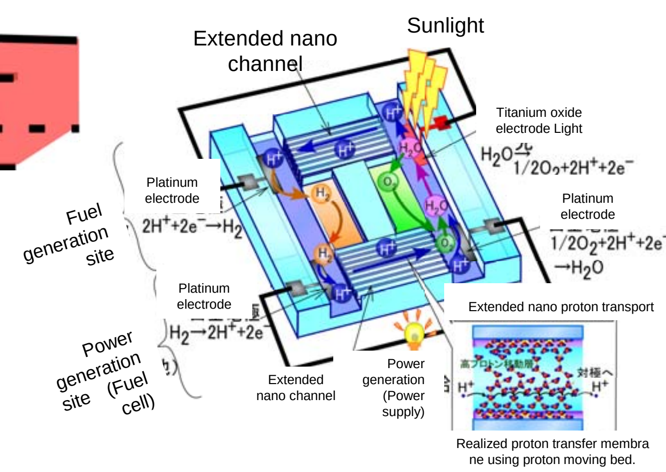




Extended nano pillar array

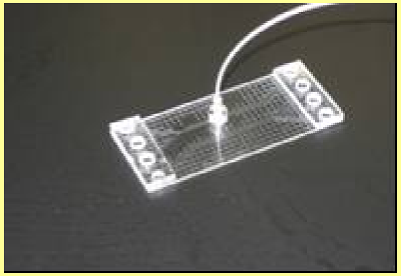
Light fuel cell

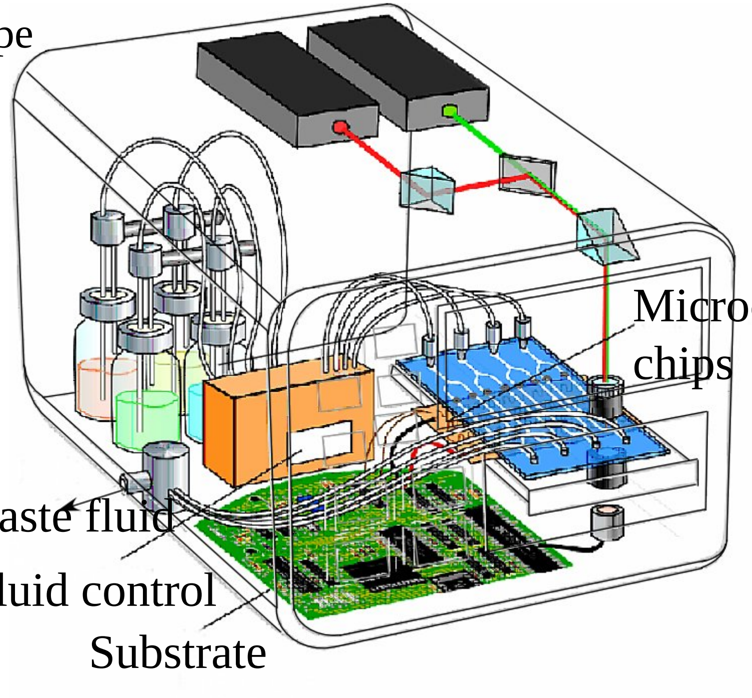
Clean fuel cell driven by light and water



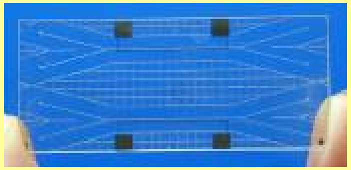
Micro-chemical-Chips-Equipped Chemical Devices

On-chip thermal lens microscope



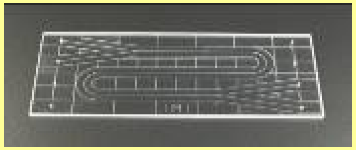


Vapor-liquid concentration chip

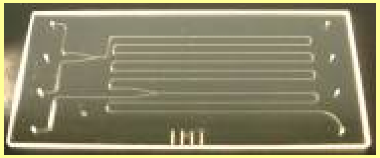


Cell cultivation chip

Liquid-liquid extraction chip



Asymmetrical epoxy chip



On-chip membrane separation

On-chip packed column

Solid-liquid extraction chip

The University-industry Cooperation and Research Topics

Basic science research	Fundamental technology research	Applied technology rese
Micro/nano chemistry	Micro/nano space chemistry	Microchemistry system

Ultrasensitive spectral analysis

Ultrasensitive spectral analysis
Micro/nano space fluid molecular theory
Micro/nano space reaction chemistry
Micro/nano interfacial fluid chemistry
Micro/cytochemistry
Micro/nano electrochemistry

Microchemistry process technology
Microchemistry process control technology
Micro-fluid device technology
Micro-fluid control technology
Micro/nano processing technology
Micro-surface technology
Micro-bioprocess technology
Micro-analysis measurement technology
Microchemical system designing technology

Micro-diagnosis system
Micro-analysis system
Micro-chemosynthesis system
Micro combinational chemistry system
Micro-bioassay system
Micro-breeding system

The University of Tokyo

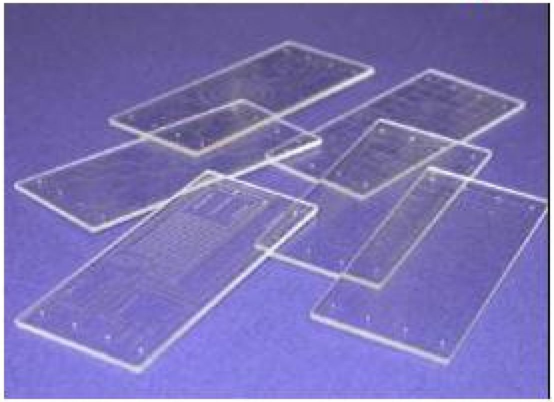
Kanagawa Academy of Science and Technology

Private enterprises (nationwide projects)

大学発ベンチャー企業
マイクロ化学技研（IMT社）による製品化

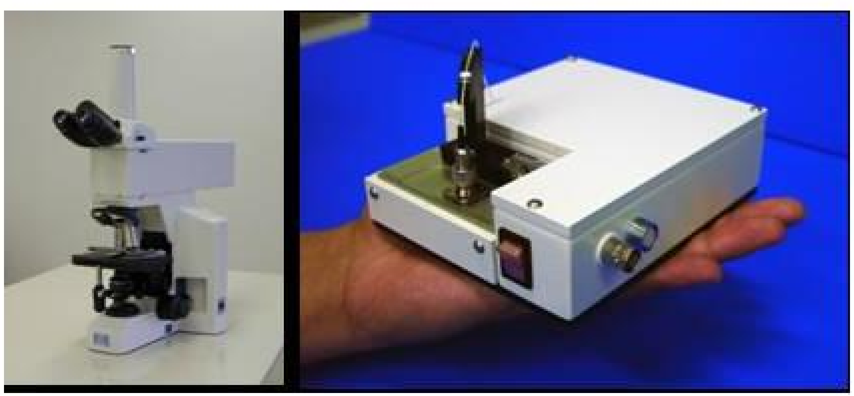
Institute of Microchemical Technology www.i-mt.co.jp

Micro Chemical Chip

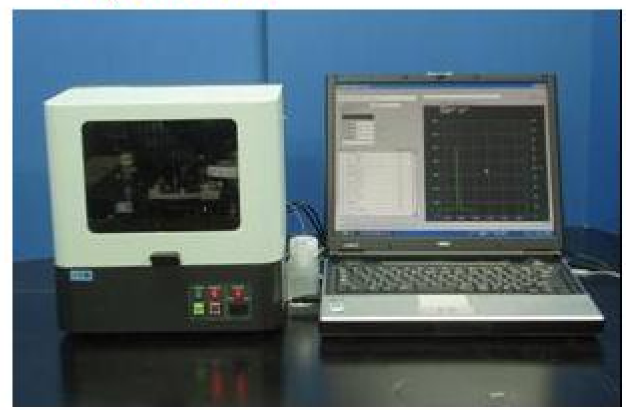


Peripheral Devices & Accessories

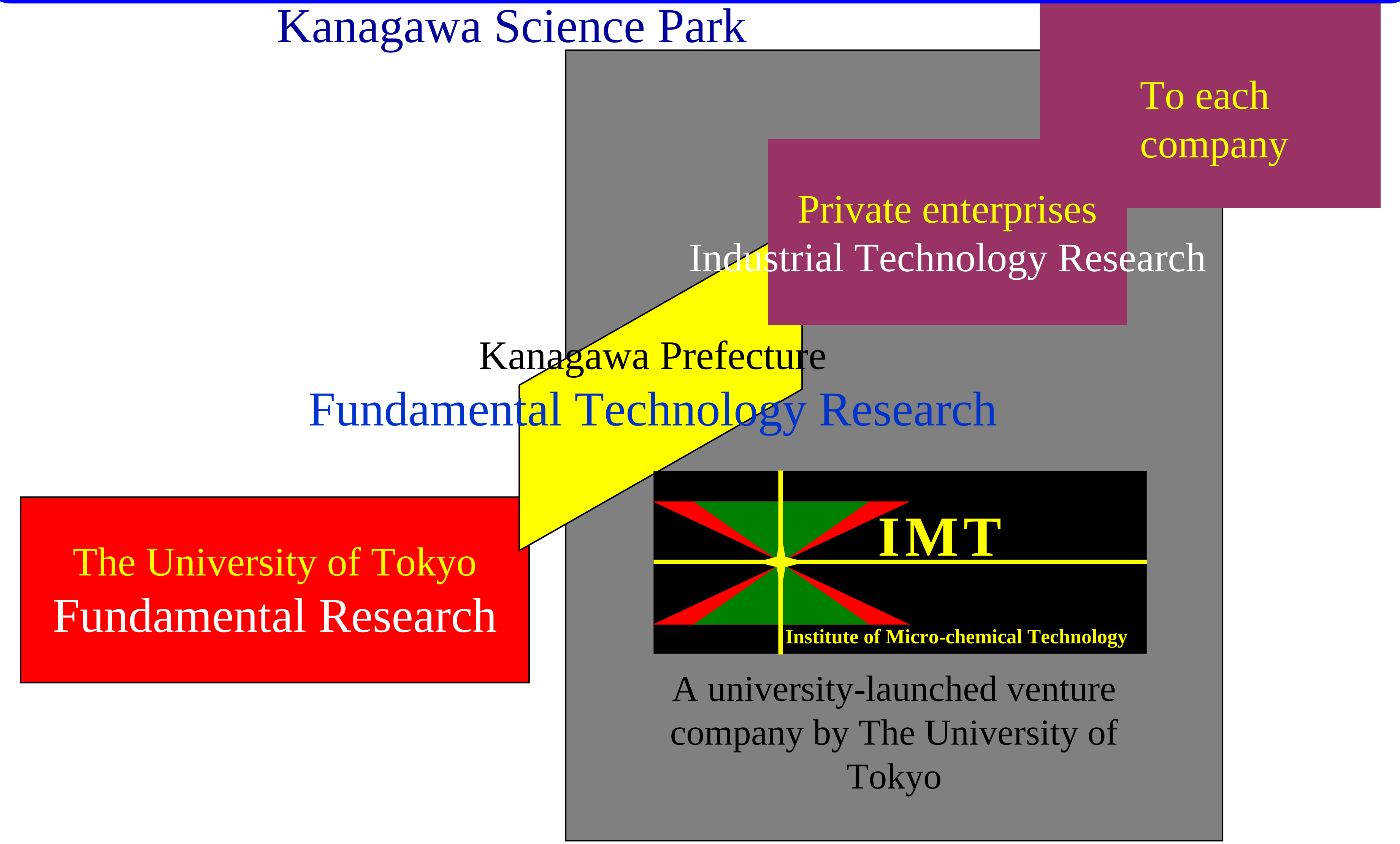
Detectors: TLM

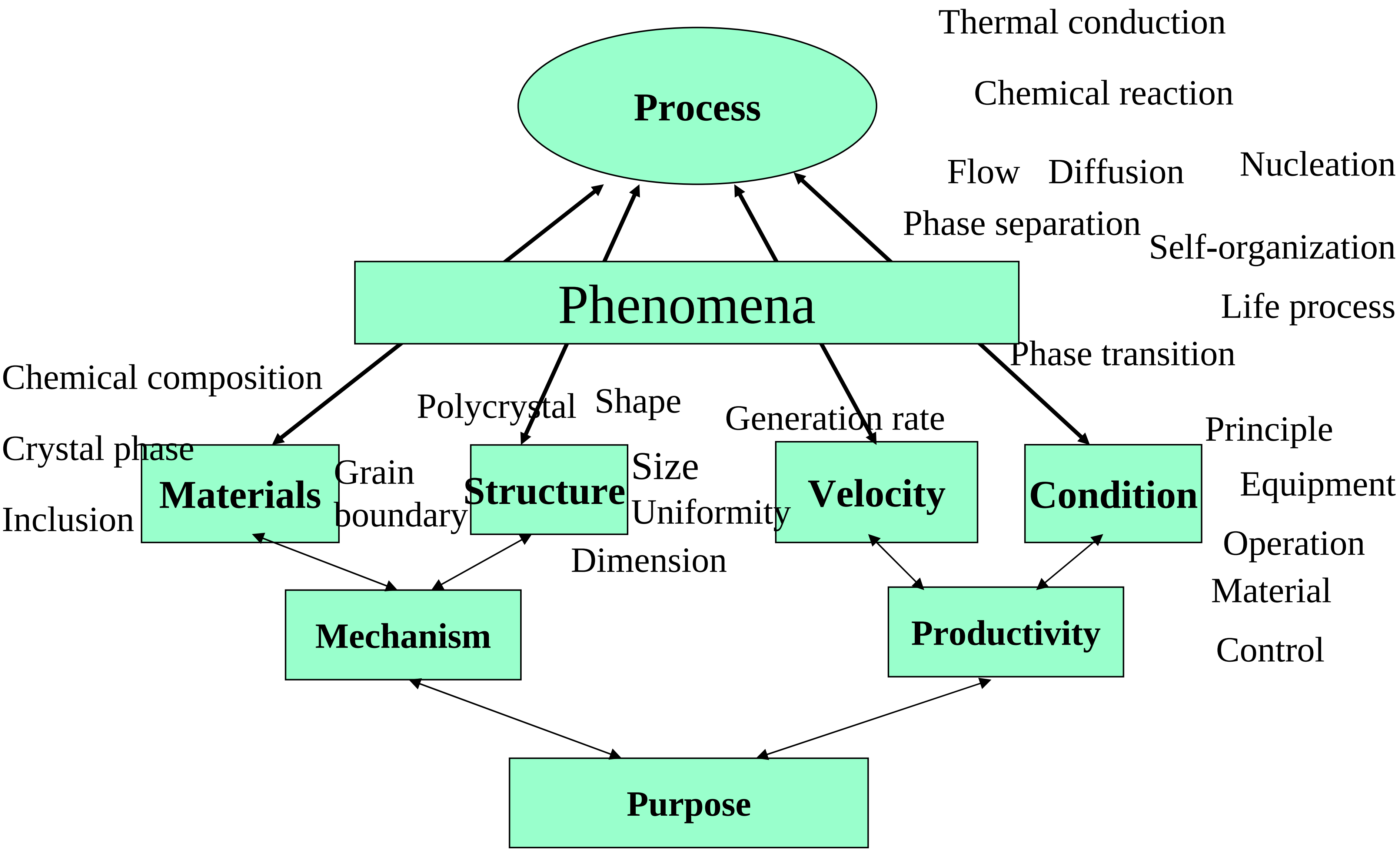


Systems



Collaboration in Research and Development (University-industry Cooperation and Regional Cooperation)





Process
Thermal conduction
Chemical reaction
Flow
Diffusion
Nucleation
Phase separation
Self-organization
Life process
Phase transition
Phenomena
Chemical composition
Crystal phase
Inclusion
Polycrystal
Grain boundary
Shape
Size
Uniformity
Dimension
Generation rate
Principle
Equipment
Operation
Material
Control
Materials
Structure
Velocity
Condition
Mechanism
Productivity
Purpose

Macroscopic Outlook for Energies in the 21st Century

Drastic improvement in energy efficiency

Transport problems of energy:

- Room-temperature superconductivity
- Microwave transport
- Chemical conversion

Solar energy generation in deserts

Katabatic wind power generation

Solar power generation by satellites

Sizes: nm μ m mm m km Mm

Matter: system device material

System Subsystem Sub-subsystem…

↑ ↑ ↑

Material-structure Material-structure Material-structure

The Meaning of "Materials" in the 21st Century

The transition of social needs:

Mass production of ordinary function products

Improvement in process efficiency

Energy saving, Conservation of resources, Environmental response, and Automation

High functionalization

New requirements:

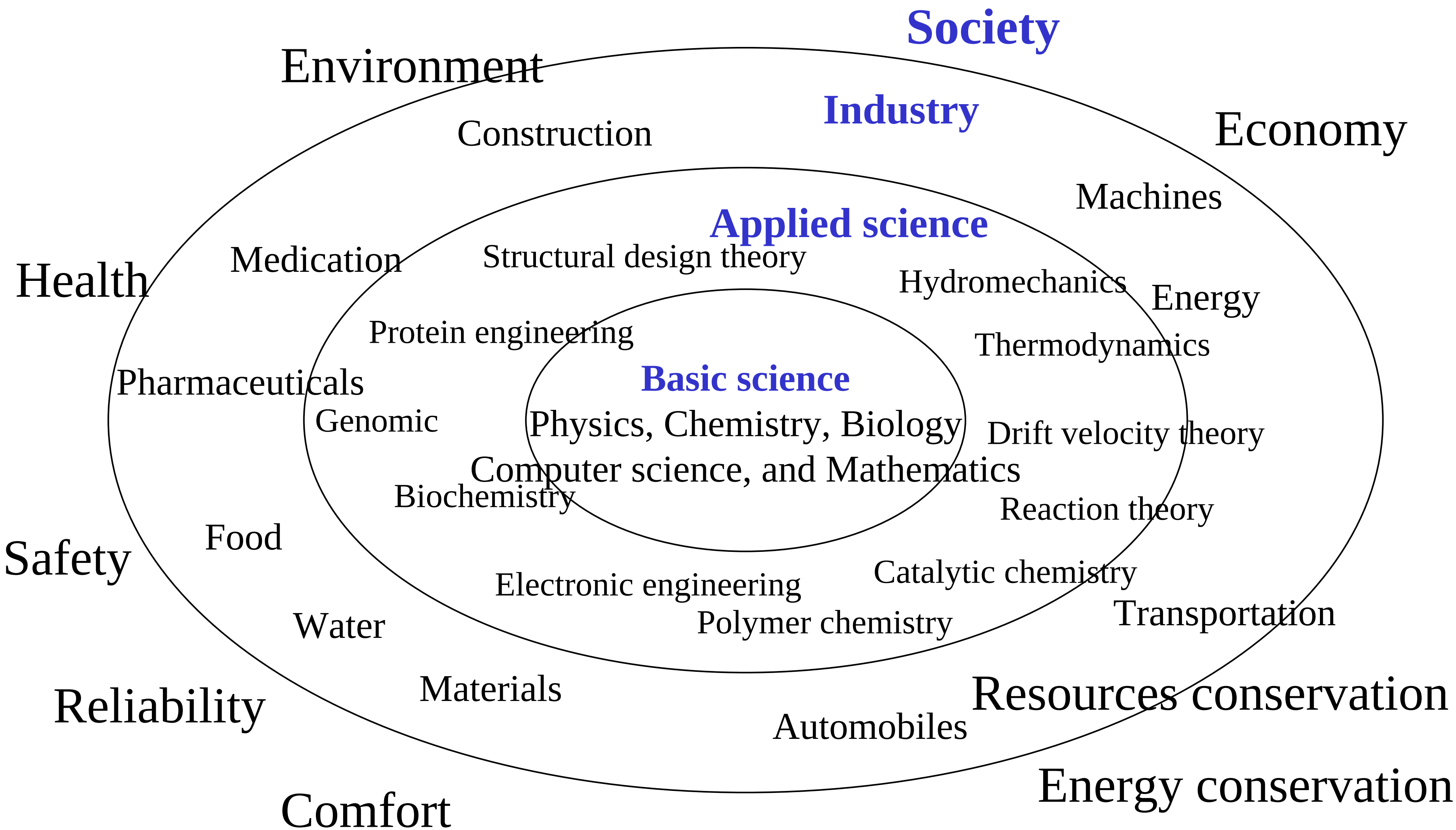
Adaptive materials for a sustainable society: energy and environment

Simultaneous achievement

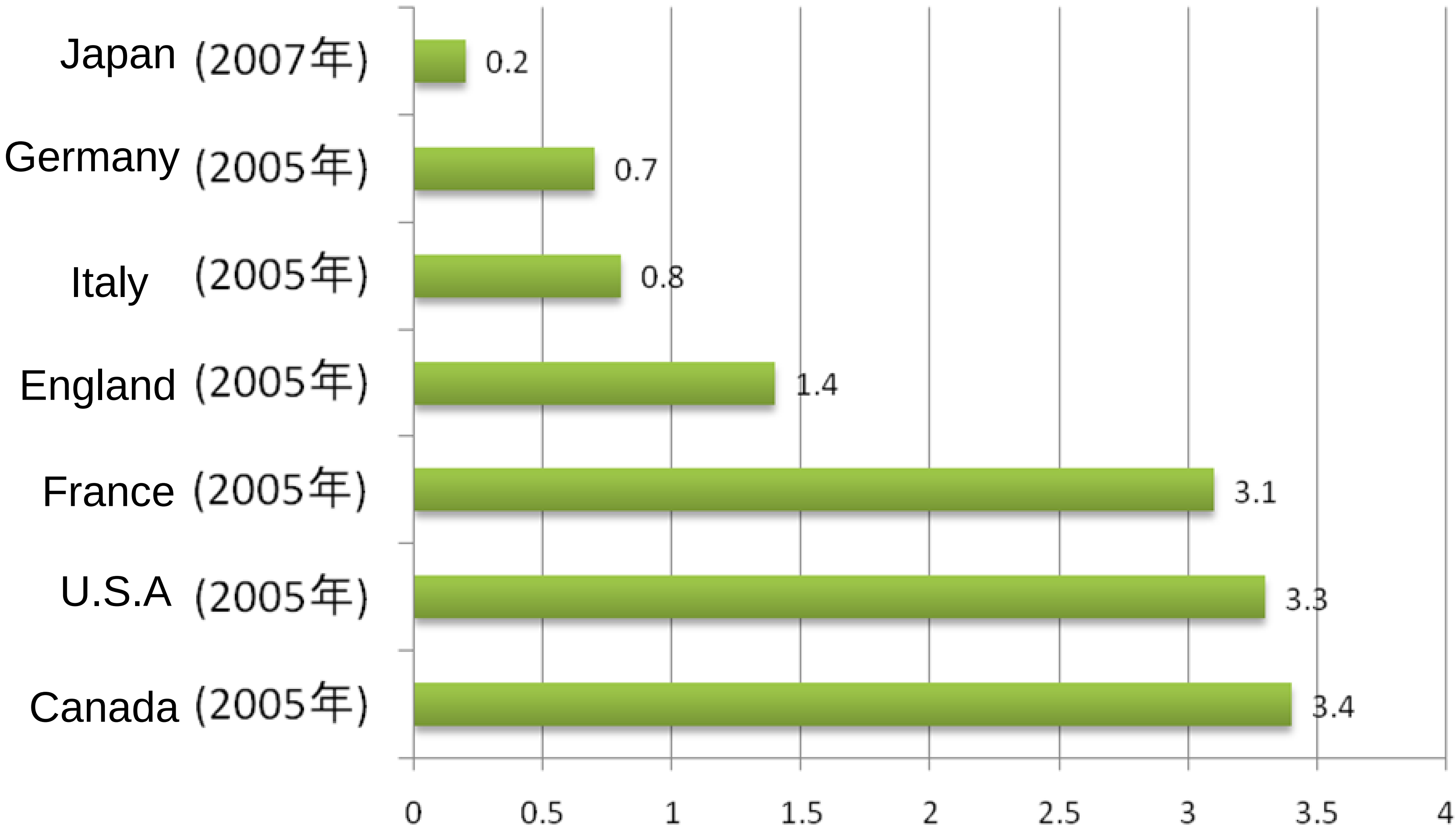
What is the role of science and technology?

To control materials and cause them to create a foundation.

Science of Materials: The University Lecture



Comparison of generation of sulfur oxides from heat power plants.



Generation rate of SOx per power generation [g/kWh]

‡ Data from Tokyo Electric Power Co.,Inc Sustainability report 2009

Japan – “A Country Meeting the Challenges of Industrialization”

Poor resources with a highly-dense population

Future image of the Earth

The success may lead Japan to become a model for the world.

On the stage of world history, Japan is expected to play a leading role.

Our country is a source of international competitiveness
and is respected by the world.

The Courage of a Leader