Lecture Note #1 (Fall, 2020)

Introduction and basic principles

1. Goal & syllabus
2. Electrochemical cells
3. Electrochemical reactions
4. Anode and cathode
5. Electric quantities and units
6. Faraday's law
7. Galvanic cell and electrolytic cell
8. Positive electrode and negative electrode

Fuller & Harb (textbook), ch.1, Pletcher & Walsh (ref.), ch.1, Bard, ch.1, Oh, ch.1

전기화학에너지공학 강의의 목표 (Goal)

- ✓ 전기화학(Electrochemistry)에 대한 기초적 지식 함양
- ✓ 전기화학의 공학 혹은 산업적 응용 기초지식 함양
- ✓ 산화와 환원의 전기화학반응을 통한 연구에의 적용 가능성 탐색
- ✓ 전기화학 역사를 통한 연구개발의 통찰력 확보
- ✓ 타분야와의 공동연구 가능성 모색을 통한 시너지 확보

강의 계획 (Syllabus)

2020 Fall, 4582-608 (WCU Program)

Electrochemical Energy Engineering, 전기화학에너지공학

LECTURER: Professor Yung-Eun Sung (**성영은**)

Office: Rm #729, Phone: 880-1889, E-mail: ysung@snu.ac.kr

OUTLINE

This class deals with electrochemical principles for the industrial electrochemistry, electrochemical engineering and technologies. After reviewing the basics of electrochemistry, this course will be continued to the applications such as electrodeposition, corrosion, electrolysis, battery, fuel cell, photoelectrochemistry, and so on. (Lecture will be provided in Korean in this Semester.)

전기화학의 기초 원리를 살펴본 다음, 이 원리가 전착, 부식, 수전해, 배터리, 연료전지, 광전기화학, 그리고 기타 전기화학 산업의 이해에 어떻게 적용되는지를 살펴본다. 전기화학 산업을 통해 전기화학을 더 깊이 이해할 필요가 있음을 보고, 또 이를 통해 학생들이 자신의 연구분야에서 응용 가능성을 찾아볼 수 있도록 하려는 것이 이 강의의 목적이다. 주로 비대면으로 이루어지는 강의에서 효율적 강의 전달을 위해 우리말로 강의가 이루어진다.

TEXTBOOK **(주교재의 내용을 다 다룰 예정임)**
Thomas F. Fuller, John N. Harb, Electrochemical Engineering, Wiley, 2018.
(*교과서의 예제(Illustration을 반드시 풀어볼 것을 추천함)

REFERENCES (참고문헌들)
Derek Pletcher, Frank C. Walsh, *Industrial Electrochemistry*, Blackie Academic & Professional, 1993.
오승모, 전기화학(3판), 자유아카데미, 2019.
Milan Paunovic, Mordechay Schlesinger, *Fundamentals of Electrochemical Deposition*, Wiley, 1998.
Denny A. Jones, *Principles and Prevention of Corrosion*, Macmillan, 1992.
Mathew M. Mench, *Fuel Cell Engines*, Wiley, 2008.
Robert A. Huggins, *Advanced Batteries*, Springer, 2009. (e-book in library, also in Korean)
Allen J. Bard, Larry R. Faulkner, *Electrochemical Methods*, Wiley, 2001

GRADING **(B^+ & above ~ 80%, B^0 & below ~ 20%, or Department guide)**
Midterm Exam 40%, Final Exam 40%, Homeworks & Attendance 20 %

LECTURE ROOM & TIME: Rm #302-509, 11:00-12:15 Mon. & Wed.
OFFICE HOUR: Rm #302-729, 13:00-16:00 Mon. & Wed.

- **TA**: Jin Ki Kwak(**곽진기**), Rm#302-1007, Tel: 880-9123, 010-7231-2340, rhkrwlsrl7@snu.ac.kr
Lee Seong Beom(**이성범**), Rm#302-1007, Tel: 880-9123, 010-4850-7207, leesb0322@snu.ac.kr

전기화학에너지공학 강의 일정

SCHEDULES (일부 수정 가능)

Introduction and basic principles (ch.1, 1 week)
Cell potential and thermodynamics (ch.2, 2 week)
Electrochemical kinetics (ch.3, 3 week)
Transport (ch.4, 4 week)
Electrode structures and configurations (ch.5, 5 week)
Analysis of electrochemical systems (ch.6, 6 week)
Electrodeposition (ch.13, 7 week)
Corrosion (ch.16, 8 week)
Industrial electrolysis (ch.14, 9 week)
Fuel cells (ch.9,10, 10,11 weeks)
Batteries (ch.7,8, 11,12 weeks)
Electrochemical capacitors (ch.11, 13 week)
Energy storage & conversion (ch.12, 14 week)
Photoelectrochemical cells (ch.15, 15 week)

전기화학 (Electrochemistry)

전기화학 (Electrochemistry):
passage of electric current → chemical changes
chemical reactions → production of electric energy

coupling of chemical changes to the passage of electricity
→ electron + ion conduction (flow of electrons & ions)
→ Electrochemical devices & technologies
→ Materials & devices & process

전기화학 반응 (electrochemical reaction):
전자가 관여된 산화(oxidation) **또는 환원**(reduction) **반응**

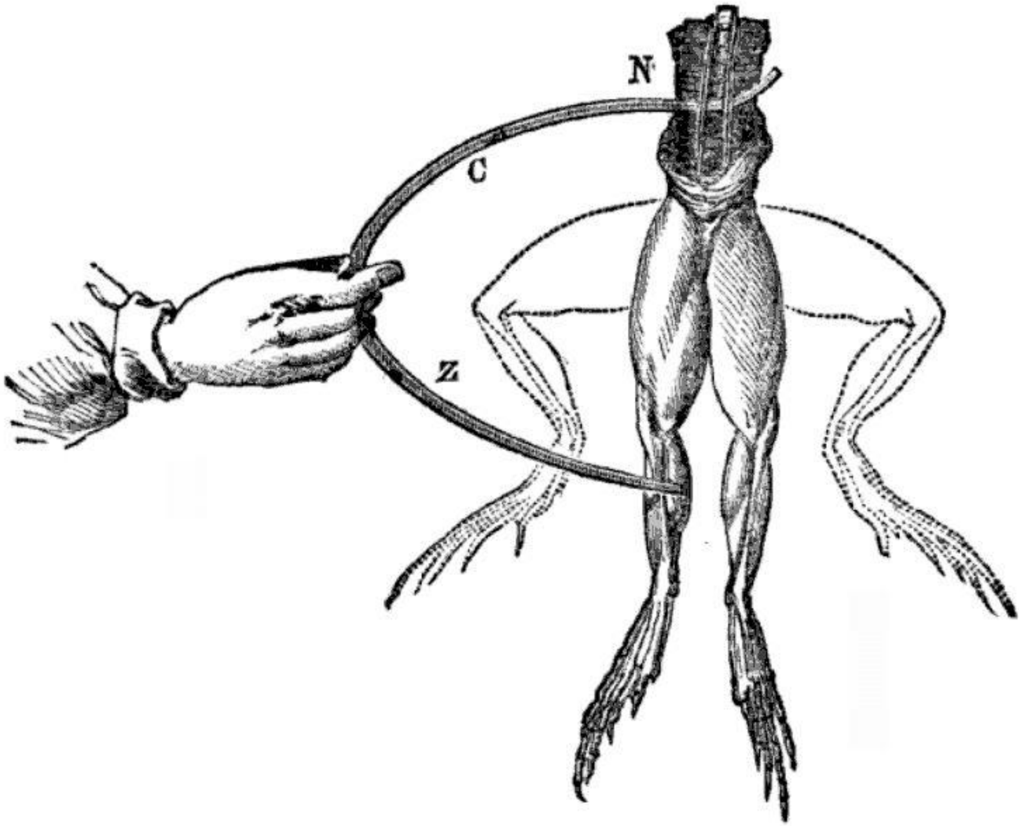
전기화학 반응의 예 (Examples)

- ✓ Battery or fuel cell: chemical state changes → electric power
- ✓ Supercapacitor: double layer phenomena → electric power
- ✓ Photoelectrochemical cell (Solar cell): photoelectrochemistry → power
- ✓ Photocatalysis: light → hydrogen or chemical reaction
- ✓ Electrochromic: chemical state changes by electric signal → coloration
- ✓ Sensors: chemical state changes by mass → electric signal
- ✓ Electrolysis: electric power → chemical species
- ✓ Electrodeposition: electric power → thin film, Cu metallization
- ✓ Electrochemical synthesis: electric power → chemical change
- ✓ Corrosion: potential difference → chemical change
- ✓ Etching

History of electrochemistry

- ✓ 탈레스(그리스, BC 600경): 호박(광물)을 모피로 마찰하면 깃털을 당긴다
  "자연에 존재하는 물체 가운데 일부는 불멸의 영혼을 가진 채 살아 있다 "
- ✓ 아리스토텔레스: 전기(?) 가오리가 먹이를 기절시키는 능력이 있다
- ✓ 1600년경 길버트(William Gilbert, 영국): 호박의 그리스어 electron(ηλεκτρον)에서 electric(전기적), electrica라는 단어 만듦. 양의 전기와 음의 전기가 있다
- ✓ 1785년 쿨롱(Coulomb, 프랑스) 양전기와 음전기가 끌어당기는 현상으로부터 쿨롱의 법칙 발견
- ✓ 1791년 갈바니(Galvani, 이탈리아): 불꽃방전이 개구리 다리를 움직이게 한다 (전류, 갈바니 전기)
- ✓ 1799년 볼타(Volta, 이탈리아): 전기 발생장치 개발(배터리, 전지)
- ✓ 데이비(Humphrey Davy, 1778-1829): 물의 전기분해시 산소발생 전극을 양극(positive), 수소발생 전극을 음극(negative)으로 제안 → 양의 전하를 띤 수소이온이 음극으로 이동
- ✓ 패러데이(Michael Faraday, 1791-1867, 영국) "전류는 양의 전하가 양의 전극에서 음의 전극으로 이동하는 것이다" 정의, 전기분해 법칙
- ✓ 1897년 톰슨 음전하를 띤 전자 발견 → 전기는 전자의 이동에 의한 것이다. 전자가 흐르는 방향이 전류가 흐르는 방향의 반대이다
- ✓ 밀리칸(1909): 전자 1개의 전하량 측정, $e = 1.602 \times 10^{-19}$ C

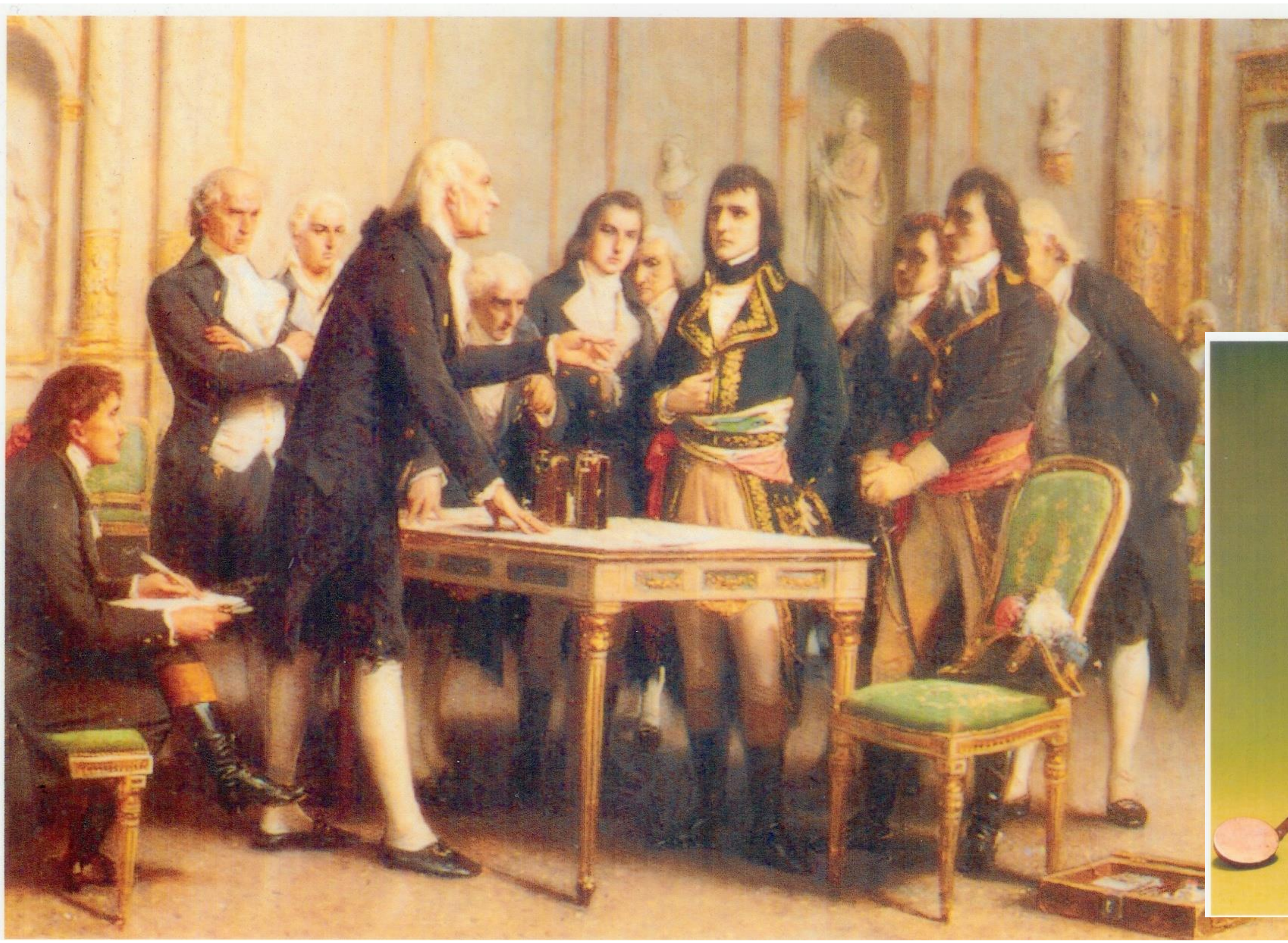
전기화학의 역사 (Galvani 실험) (History)



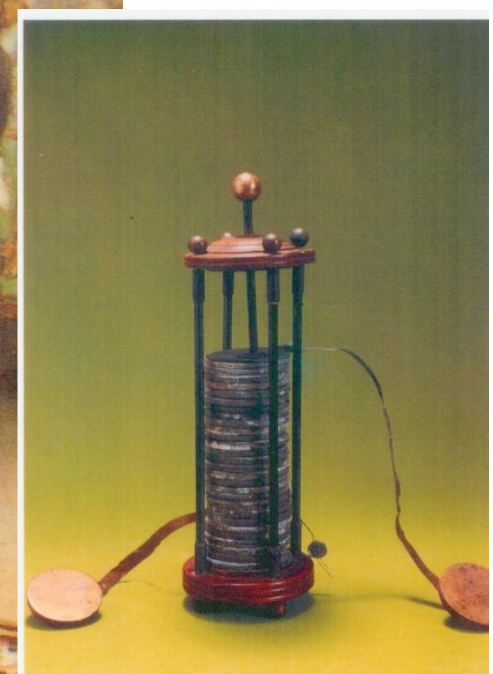
개구리 뒷다리 실험

Gavani를 기려 Galvanic cell 명명
심장박동기

전기화학의 역사 (1800년 볼타) (History)



Volta



최초의 전지(배터리)

Volta를 기려 voltage, volt 명명

Volta 논문 (History)

XVII. *On the Electricity excited by the mere Contact of conducting Substances of different kinds. In a Letter from Mr.* Alexander Volta, *F. R. S. Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir* Joseph Banks, *Bart. K. B. P. R. S.*

Read June 26, 1800.

A Côme en Milanois, ce 20me Mars, 1800.

Après un long silence, dont je ne chercherai pas à m'excuser, j'ai le plaisir de vous communiquer, Monsieur, et par votre moyen à la Société Royale, quelques resultats frappants auxquels je suis arrivé, en poursuivant mes expériences sur l'électricité excitée par le simplé contact mutuel des métaux de différente espèce, et même par celui des autres conducteurs, aussi différents entr'eux, soit liquides, soit contenant quelque humeur, à laquelle ils doivent proprement leur pouvoir conducteur. Le principal de ces resultats, et qui comprend à-peu-près tous les autres, est la construction d'un appareil qui ressemble pour les effets, c'est-à-dire, pour les commotions qu'il est capable de faire éprouver dans les bras, &c. aux bouteilles de Leyde, et mieux encore aux batteries électriques foiblement chargées, qui agiroient cependant sans cesse, ou dont la charge, après chaque explosion, se rétabliroit d'elle-même; qui jouiroit, en un mot, d'une charge indéfectible, d'une action sur le fluide électrique, ou impulsion, essentiellement, et

From: *Philosophical Transactions, of the Royal Society of London*. For the Year MDCCC. Part I. London, printed by W. Bulmer and Co. Cleveland-row, St. James's; and sold by Peter Elmsly, Printer to the Royal Society. MDCCC, pp. 403-431.

THE

PHILOSOPHICAL MAGAZINE.

SEPTEMBER 1800.

I. *On the Electricity excited by the mere Contact of conducting Subſtances of different Kinds. In a Letter from Mr.* Alexander Volta, *F.R.S. Profeſſor of Natural Philoſophy in the Univerſity of Pavia, to the Right Hon. Sir* Joseph Banks, *Bart. K.B. P.R.S.**

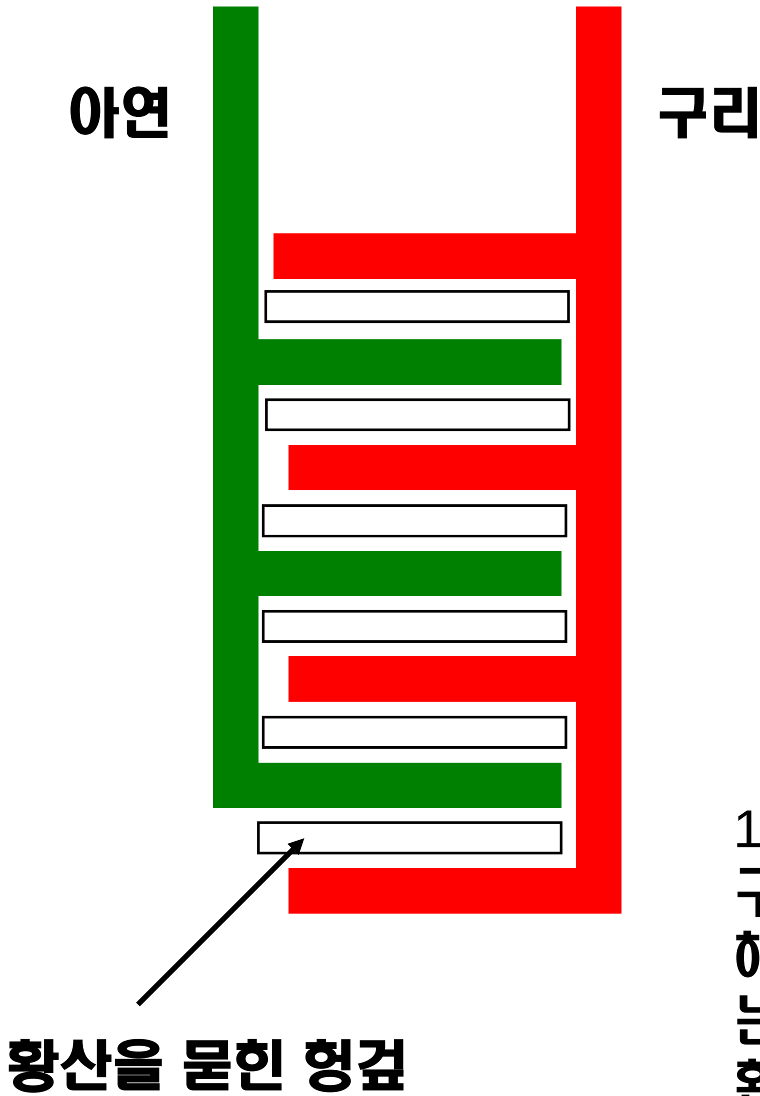
Como in the Milaneſe, March 20, 1800.

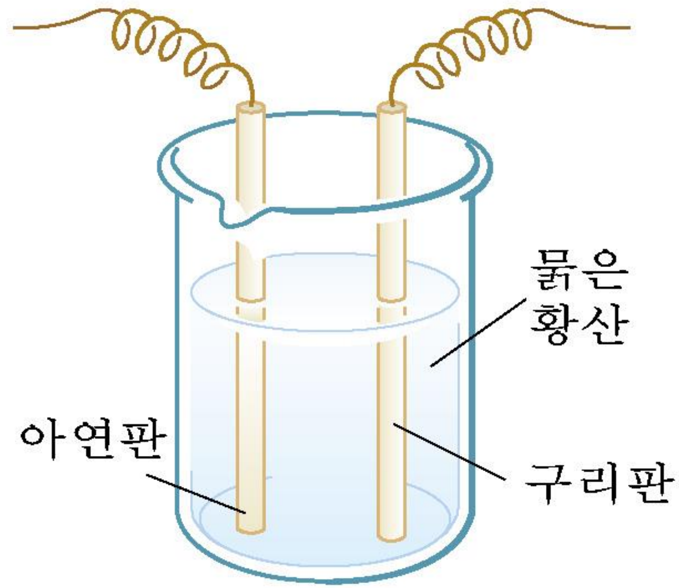
After a long ſilence, for which I ſhall offer no apology, I have the pleaſure of communicating to you, and through you to the Royal Society, ſome ſtriking reſults I have obtained in purſuing my experiments on electricity excited by the mere mutual contact of different kinds of metal, and even by that of other conductors, alſo different from each other, either liquid or containing ſome liquid, to which they are properly indebted for their conducting power. The principal of theſe reſults, which comprehends nearly all the reſt, is the conſtruction of an apparatus having a reſemblance in its effects (that is to ſay, in the ſhock it is capable of making the arms, &c. experience) to the Leyden flaſk, or, rather, to an electric battery weakly charged acting inceſſantly, which ſhould charge itſelf after each exploſion; and, in a word, which ſhould have an inexhauſtible charge, a perpetual action or impulſe on the electric fluid; but which differs from it eſſentially both by this continual action, which is peculiar

* Tranſlated from the author's paper publiſhed in French in the Philoſophical Tranſactions for 1800, part 2.

to

볼타 전지 (1800년)





✓ **산화** : $Zn \rightarrow Zn^{2+} + 2e^{-}$

✓ **환원** : $2H^{+} + 2e^{-} \rightarrow H_2$

1800년 이탈리아의 볼타가 발명한 전지. 구리를 양극, 아연을 음극, 황산 용액을 전해액으로 한다. 전압은 약 1.1V. 음극에서는 아연이 녹고, 양극에서는 수소 이온이 환원되어서 수소 가스가 발생

산화와 환원

Indicate in the following reactions which are reductions and which are oxidations:

(1) $Fe^{2+} + 2e^- \rightarrow Fe$ (2) $Cl^- \rightarrow 1/2Cl_2 + e^-$ (3) $Fe^{2+} \rightarrow Fe^{3+} + e^-$

(4) $CrO_4^{2-} + 3e^- \rightarrow Cr^{3+}$ (5) $O_2 + 4e^- \rightarrow 2O^{2-}$ (6) $Br_2 + 2e^- \rightarrow 2Br^-$

Basic concepts of electrochemistry

- An electrochemical reaction is a heterogeneous chemical process involving the transfer of charge to or from an electrode, generally a metal, carbon or a semiconductor

- Cathodic process: reduction by the transfer of electrons from an electrode (cathode, 환원극, 환원전극)

$$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$$

$$Cu^{2+} + 2e^- \longrightarrow Cu$$

$$Na^+ + e^- + Hg \longrightarrow NaHg$$

$$2CH_2 = CHCN + 2H_2O + 2e^- \longrightarrow (CH_2CH_2CN)_2 + 2OH^-$$

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \longrightarrow PbSO_4 + 2H_2O$$

- Anodic process: oxidation by the removal of electrons to the electrode

$$2H_2O - 4e^- \longrightarrow O_2 + 4H^+$$

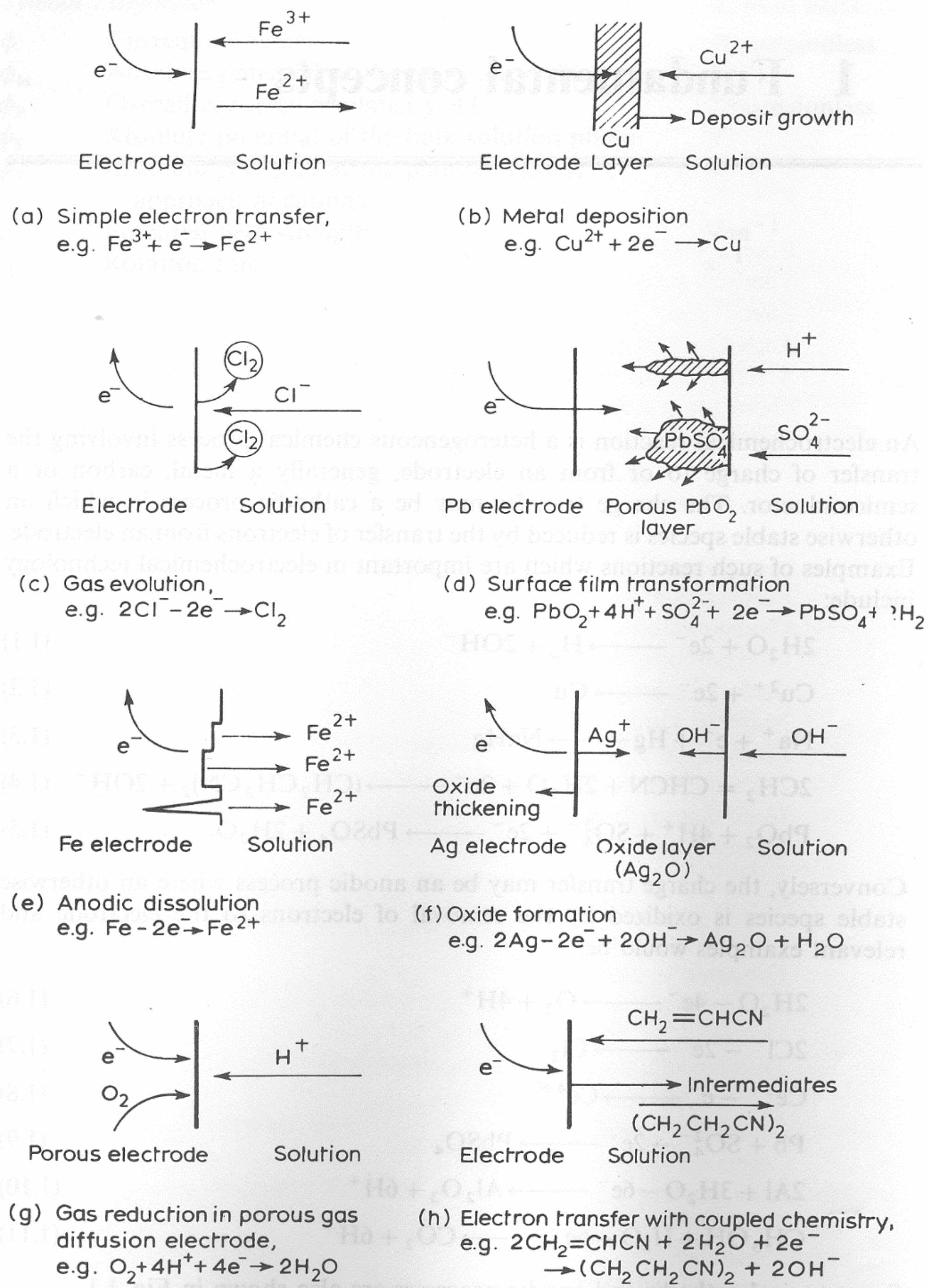
$$2Cl^- - 2e^- \longrightarrow Cl_2$$

$$Ce^{3+} - e^- \longrightarrow Ce^{4+}$$

$$Pb + SO_4^{2-} - 2e^- \longrightarrow PbSO_4$$

$$2Al + 3H_2O - 6e^- \longrightarrow Al_2O_3 + 6H^+$$

$$CH_3OH + H_2O - 6e^- \longrightarrow CO_2 + 6H^+$$



(a) Simple electron transfer, e.g. $Fe^{3+} + e^- \rightarrow Fe^{2+}$

(b) Metal deposition e.g. $Cu^{2+} + 2e^- \rightarrow Cu$

(c) Gas evolution, e.g. $2Cl^- - 2e^- \rightarrow Cl_2$

(d) Surface film transformation e.g. $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2$

(e) Anodic dissolution e.g. $Fe - 2e^- \rightarrow Fe^{2+}$

(f) Oxide formation e.g. $2Ag - 2e^- + 2OH^- \rightarrow Ag_2O + H_2O$

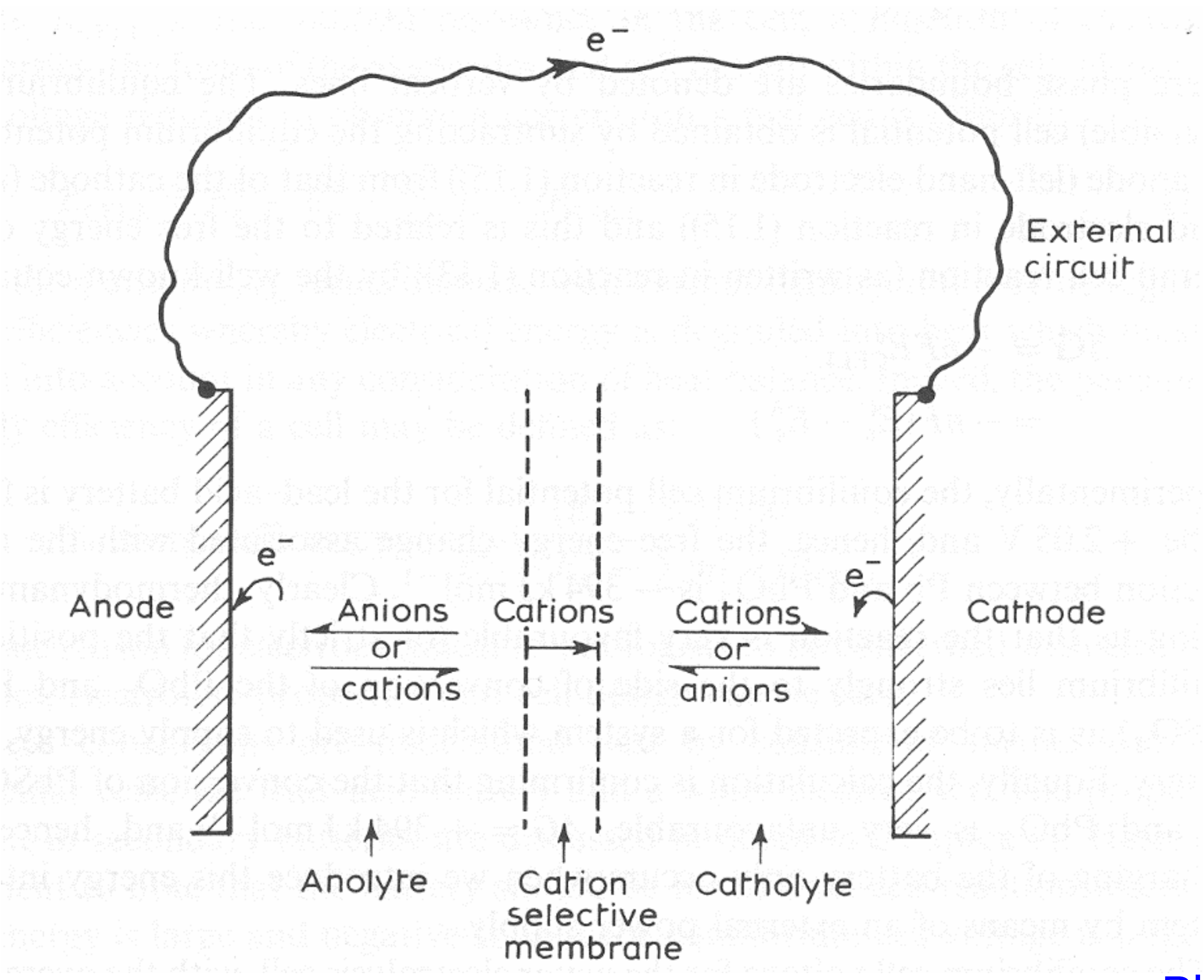
(g) Gas reduction in porous gas diffusion electrode, e.g. $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

(h) Electron transfer with coupled chemistry, e.g. $2CH_2{=}CHCN + 2H_2O + 2e^- \rightarrow (CH_2CH_2CN)_2 + 2OH^-$

Pletcher, Fig.1.1

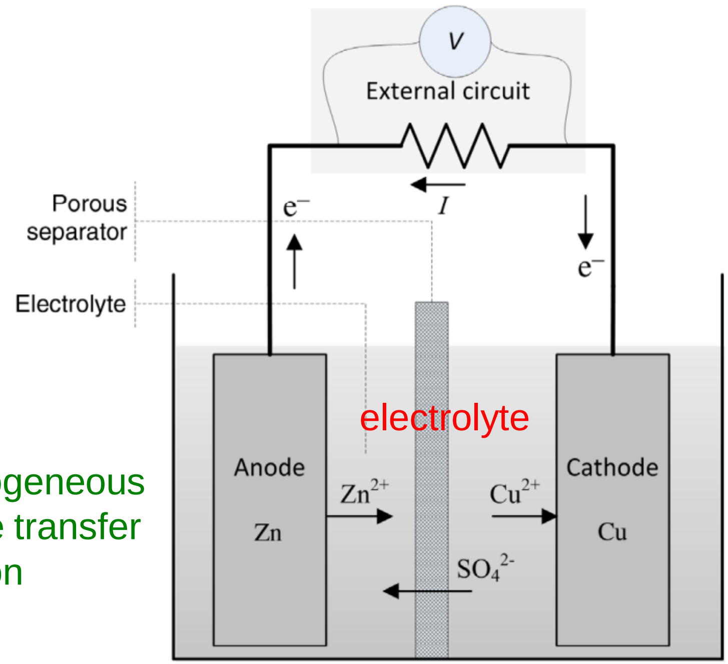
Electrochemical cell

- Electrochemical cell : contains anode and cathode, the amount of reduction at the cathode and oxidation at the anode must be equal



Pletcher, Fig.1.2

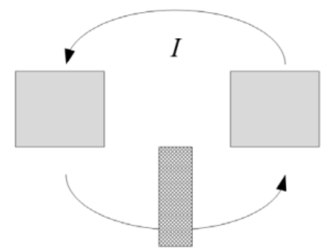
- Daniel cell (1836): contains anode and cathode, the amount of reduction at the cathode and oxidation at the anode must be equal



Heterogeneous charge transfer reaction

Half-cell reaction $Zn \rightarrow Zn^{2+} + 2e^-$ $Cu^{2+} + 2e^- \rightarrow Cu$

anode cathode

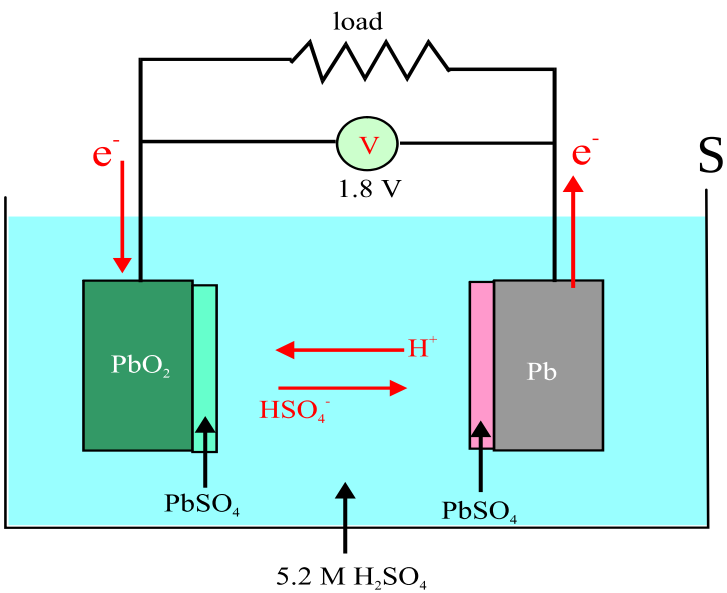


$$\sum I = 0$$

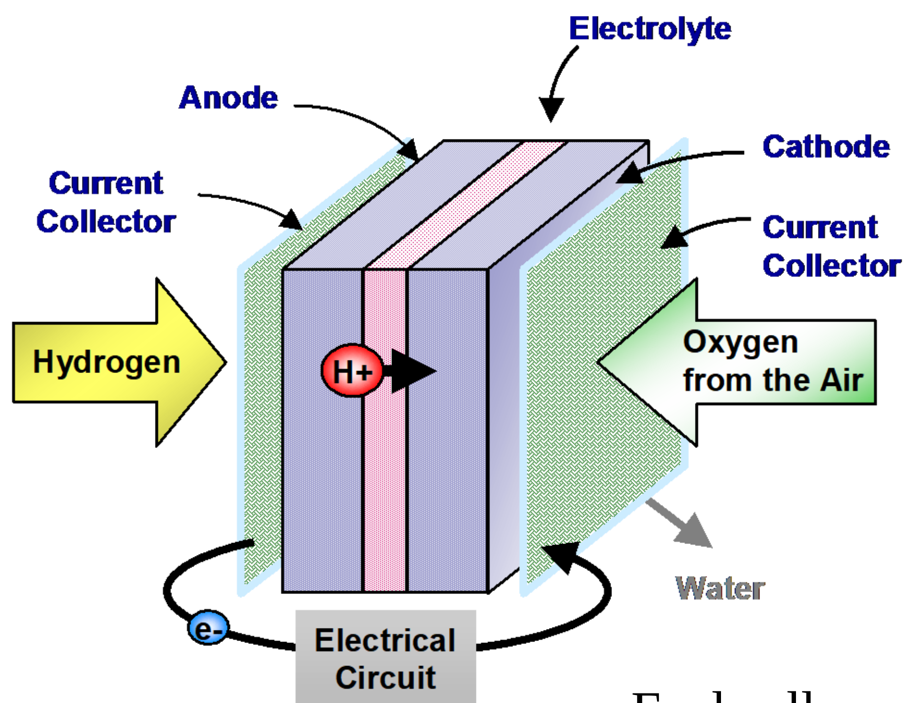
Figure 1.1 A Daniell cell is an example of an electrochemical cell. During steady operation, a constant current flows throughout the cell. For any given volume, the current entering and leaving must sum to zero since charge is conserved.

Full-cell reaction: $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

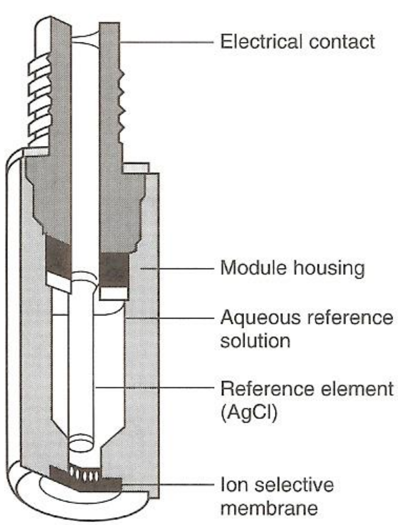
Electrochemical Cell



Solution electrochemistry

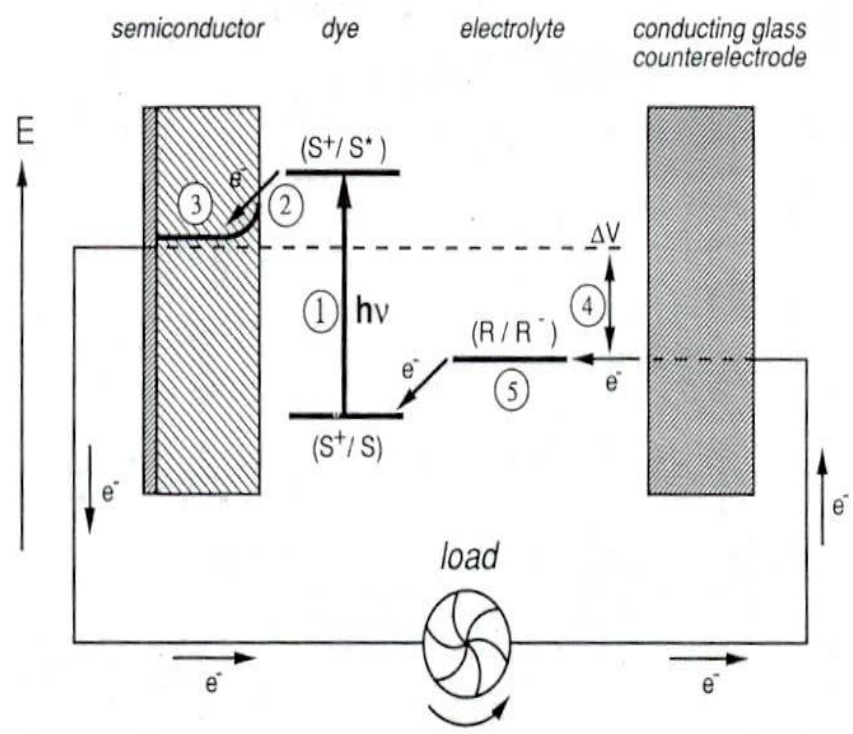


Fuel cell



pH meter (sensor)

Battery



Photoelectrochemical cell
(dye-sensitized solar cell)

Characteristics of electrochemical reactions

- Separation of the oxidation (anodic) and reduction (cathodic) reactions
- Use of electrons to perform work
- Direct measurement of reaction rates by measuring electric current
- Control of the direction and rate of reaction

전기화학 반응의 특징 (Oh, ch.1)

- 전극 전위는 전극 내부에 존재하는 전자 에너지의 표현이다
- 전기화학 반응은 전극 표면 근처에서만 가능하다
- 전기화학 반응은 여러 단계를 거쳐서 진행된다
- 전류는 반응 속도의 표현이다
- 전류는 전기화학 셀 내에서 닫힌 고리(closed loop)를 형성하며 흐른다
- 전하 전달이 전체 속도를 결정할 경우 전극 전위를 변화시켜 전류의 크기를 조절할 수 있다
- 전극 전위와 전류를 동시에 조절할 수 없다
- 물질 전달이 전체 속도를 결정할 경우 전류는 물질 전달 속도에 의해 결정된다

Electrochemical systems

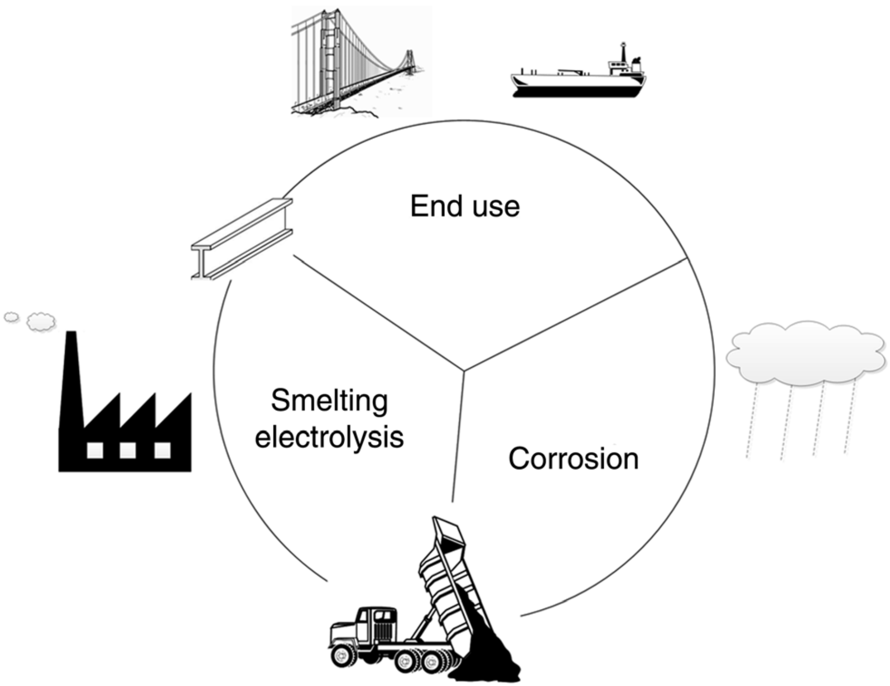


Figure 1.2 Life cycle of metals. Many of the processes are electrochemical.

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering

Electrical quantities

(1) Electric charge & current

Electric charge (= amount of electricity), q (unit: Coulomb, C), time t
Electric current, I (unit: ampere (A)):

$$I = dq/dt$$

$$q = \int I dt$$

Current density (unit: A/cm^2): i = I/A, A: surface of area

Ammeter: measuring current

Circuit: electric current flows in a closed path

(2) **Electrical potential & electric field**

Electrical potential (unit; volts, V), ϕ: the pressure of the electric fluid

Voltage: the electrical potential difference ($\Delta\phi$)

Voltmeter: measuring an electrical potential difference

Electric field strength, **E** (unit: V/m)

$$\mathbf{E} = -d\phi/dx$$

Electric field strength,

$$\mathbf{E} = \mathbf{F}/q = (1/4\pi\varepsilon\varepsilon_0)(q'/r^2)$$

예: 단위전하의 전하량 $q = 1.6 \times 10^{-19}$ C, 물의 유전상수 $\varepsilon = 78.5$, 진공 유전율 $\varepsilon_0 = 8.85 \times 10^{-12}\ C^2N^{-1}m^{-2}$, 전기이중층간의 거리 $r = 10^{-9}$ m
→ $E = 2 \times 10^7$ V/m (매우 높은 전기장) → 전위차 $\Delta\varphi = 20$ mV

(3) Ohm's law: most conductors obey this law
Current density is proportional to the field strength

$$i \propto X$$

$$i = \kappa X = -\kappa\, d\phi/dx$$

κ; electrical conductivity (siemens/m, S = A/V), $1/\kappa$; resistivity

$$\Delta\phi = -RI$$

R; resistance (unit of ohm), G; conductance,

$$G = 1/R = \kappa A/L = -I/\Delta\phi$$

L; conductor length, A; cross section
Ohm's law does not have universal validity. It does not apply to electrochemical cells.
Resistor: a device that is fabricated to have a stable and known resistance

$$\text{Power (watts)} = I^2R$$

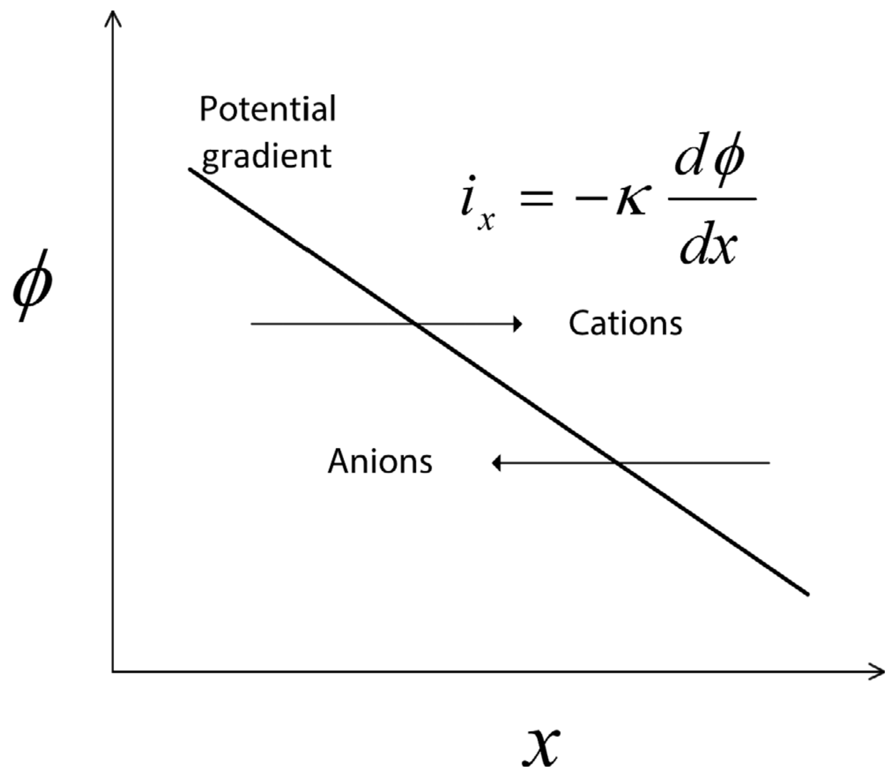


Figure 1.3 Gradient in potential and flow of current. Current flow is from left to right.

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering

(4) Power

Power: the time rate of doing work or of expending energy

Power = energy/time = work/time

Instantaneous power $P = dW/dt$

Average power $P = W/t$

Unit: watt (W) = J/s

1 horsepower (HP) = 746 W

Power ratings of various devices & animals

10^{18} W solar power input to earth

10^{12} W electricity capacity in USA (2000)

10^{9} W large electric power plant

10^{7} W train

10^{5} W automobile

1000 W horse

100 W man/woman resting

0.1~1 W Si solar cell

0.01 W human heart

에너지 저장(배터리)와 에너지 변환(연료전지)

전기차 (배터리) 300 km driving distance

40 kWh battery, Power 90 kW
(Energy density 140 Wh/kg, Power density 250 W/kg)
Battery weight 300 kg
Efficiency 7 km/kWh

수소차 (연료전지) 460 km driving distance

Power 113 kW
Power density 3 kW/l, 2kW/kg
FC weight 56 kg + (5 kg H_2 in tank (87 kg))
Efficiency 6 km/kWh

cf. Gasoline engine: ~800 km, 60~70 *liter* tank, 12 km/*liter*

전기화학 용어와 단위

용어	단위
Current (I)	Ampere (A)
Current density (i)	Ampere per m^2 (A/m^2)
Electric charge (q)	Coulomb (C = A·s)
Charge density (ρ)	Coulomb per m^3 (C/m^3)
Potential (ϕ)	Volt (V = J/C, or A·Ω)
Field strength (**E**)	Volt per meter (V/m)
Conductivity (κ)	Siemens per meter (S/m)
Resistance (R)	Ohm (Ω =1/S = V/A)
Conductance (G)	Siemens (S = A/V)
Permittivity (ε)	Farad per meter (F/m = C/V·m)
Energy (w)	Joule (J = V·C)
Power	Watt (W = J/s = A·V)
Capacitance (C)	Farad (F = C/V)

Faraday's law (패러데이 법칙)

charge(Q, C(1 C = 6.24 x 10^{18} e^-) vs. extent of chemical reaction
"the passage of 96485.4 C causes 1 equivalent of reaction (e.g., consumption of 1 mole of reactant or production of 1 mole of product in a one-electron rxn)"

$$F = N_A Q_e = (6.02 \times 10^{23}\ mol^{-1})(1.6022 \times 10^{-19}\ C) = 96{,}485\ C \cdot mol^{-1}$$

F: **패러데이 상수**

전하량 $Q = nFN$ **패러데이 법칙**

N: **반응 혹은 생성 몰수** (N = m/M), n: **반응에 참여한 전자의 수**

전류(I) = dQ/dt = nF(dN/dt) [**단위**: A = C/s]

반응속도 (mol/s) = dN/dt = i/nF

- Current (i) : the rate of the electrode reactions
- Charge (q or Q) → extent of chemical change at each electrode. The charge required to convert m mol of starting material to product in an ne^- electrode reaction is calculated using Faraday's law of electrolysis

$$q = \int i dt = mnF / M \qquad \text{for time t}$$

where F: Faraday constant (96485 C mol^{-1})

e.g. if the current is 1 A for $2H^+ + 2e^- \rightarrow H_2$

1) Current: 1 A = 1 C/s
2) Mole of electron: $1\ C/s \times \frac{1}{96485\ C/mol} = 1.036 \times 10^{-5}\ mol/s$
3) Mole of H_2: $1.036 \times 10^{-5} mol/s \times \frac{1}{2} = 5.182 \times 10^{-6} mol/s$

$$i(\text{amperes}) = \frac{dQ}{dt}(\text{coulombs/s})$$

$$\frac{Q}{nF}\frac{(\text{coulombs})}{(\text{coulombs/mol})} = N(\text{mol electrolyzed})$$

$$\text{Rate (mol/s)} = \frac{dN}{dt} = \frac{i}{nF}$$

Mass of I species

$$m_i = M_i Q / nF$$

m_i: mass, M_i: molecular weight

Illustration 1.2, 1.3, 1.4

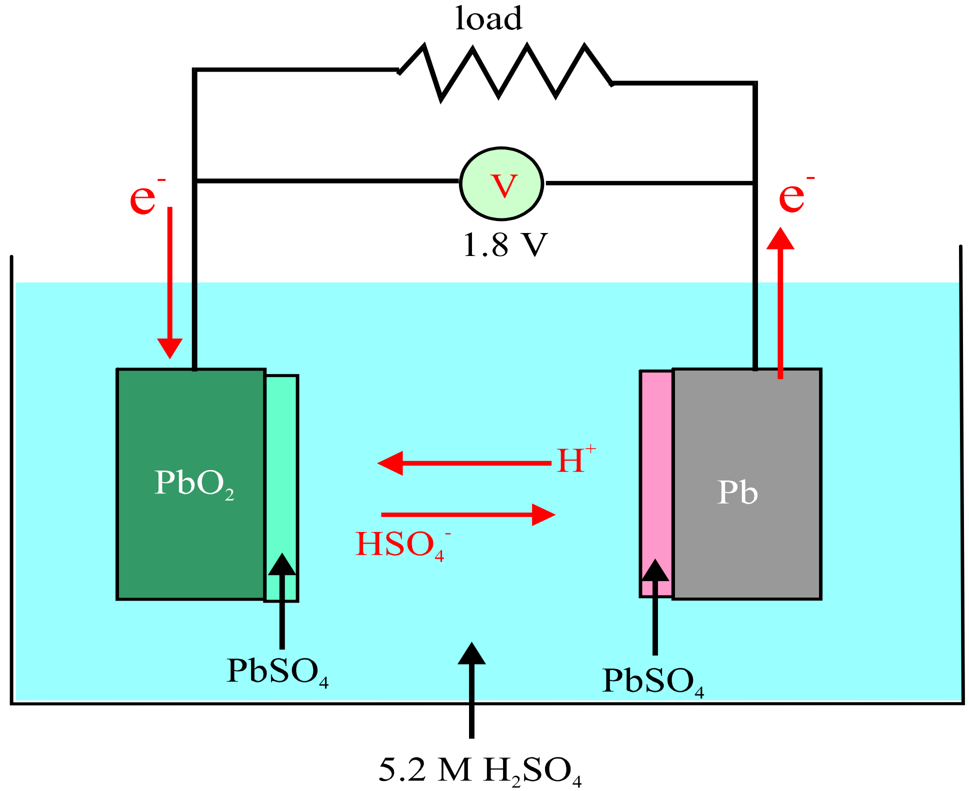
Faradaic efficiency

$$\eta_f = \frac{\text{amount of desired material produced}}{\text{amount that could be produced with the coulombs supplied}}$$

Illustration 1.5, 1.6

Electrochemical system

e.g., lead/acid cell (car battery)

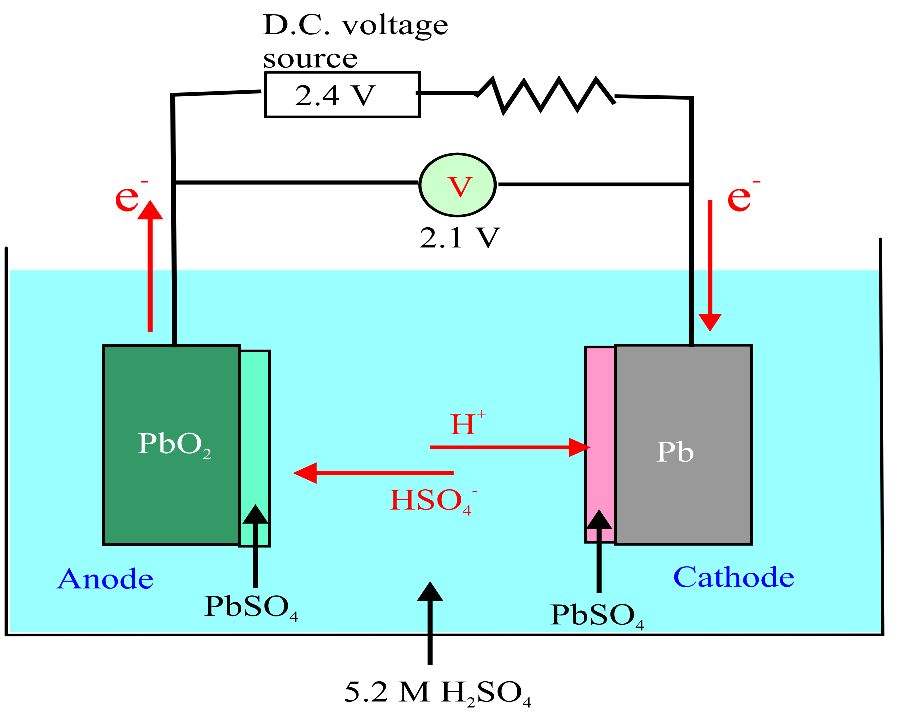


Anode: $Pb(s) + SO_4^{2-}(aq) \rightarrow 2e^- + PbSO_4(s)$
Cathode: $PbO_2(s) + SO_4^{2-}(aq) + 4H^+(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l)$
Cell: $PbO_2(s) + Pb(s) + 2H^+(aq) + 2HSO_4^-(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$

Right-hand electrode: electrons produced: **oxidation**, "**anode**" **음극**
Left-hand electrode: electrons consumed; **reduction**, "**cathode**" **양극**

2.0 V without current flow, 1.8 V with current flow (load); "**polarization**"
Galvanic cell: a cell which provides energy in this way, "**discharge**" **방전**

“**charge**”: current flow in the opposite direction by using an external source; **Electrolytic cell**; opposite direction to its spontaneous motion
PbO_2 : anode, Pb: cathode



2.0 V; perfect balance between the applied and cell voltages, no current flow → equilibrium cell voltage or reversible cell voltage or null voltage or rest voltage or “open-circuit voltage (OCV)”(since no current flows, it makes no difference if the circuit is interrupted, as by opening the switch)

Types of electrochemical cells

(i) Galvanic cell: reactions occur spontaneously at the electrodes when they are connected externally by a conductor. Converting chemical energy into electrical energy. e.g., primary battery, secondary battery (discharging), fuel cell

(ii) Electrolytic cell: reactions are effected by an external voltage. Electrical energy to chemical reactions. e.g., electrolytic syntheses, electrorefining (e.g., copper), electroplating, secondary battery (charging)

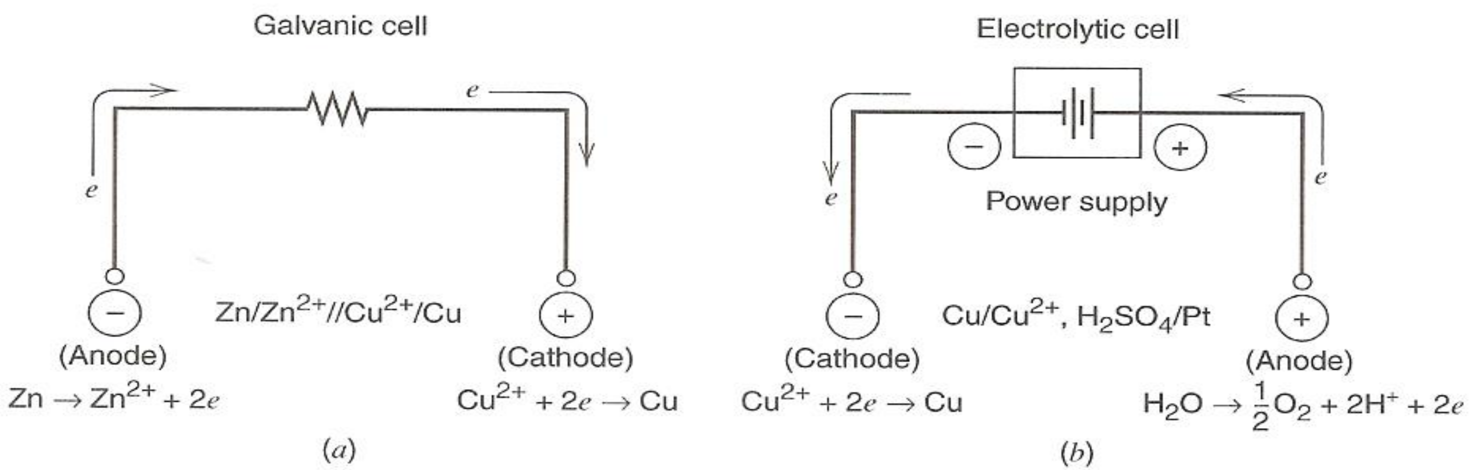
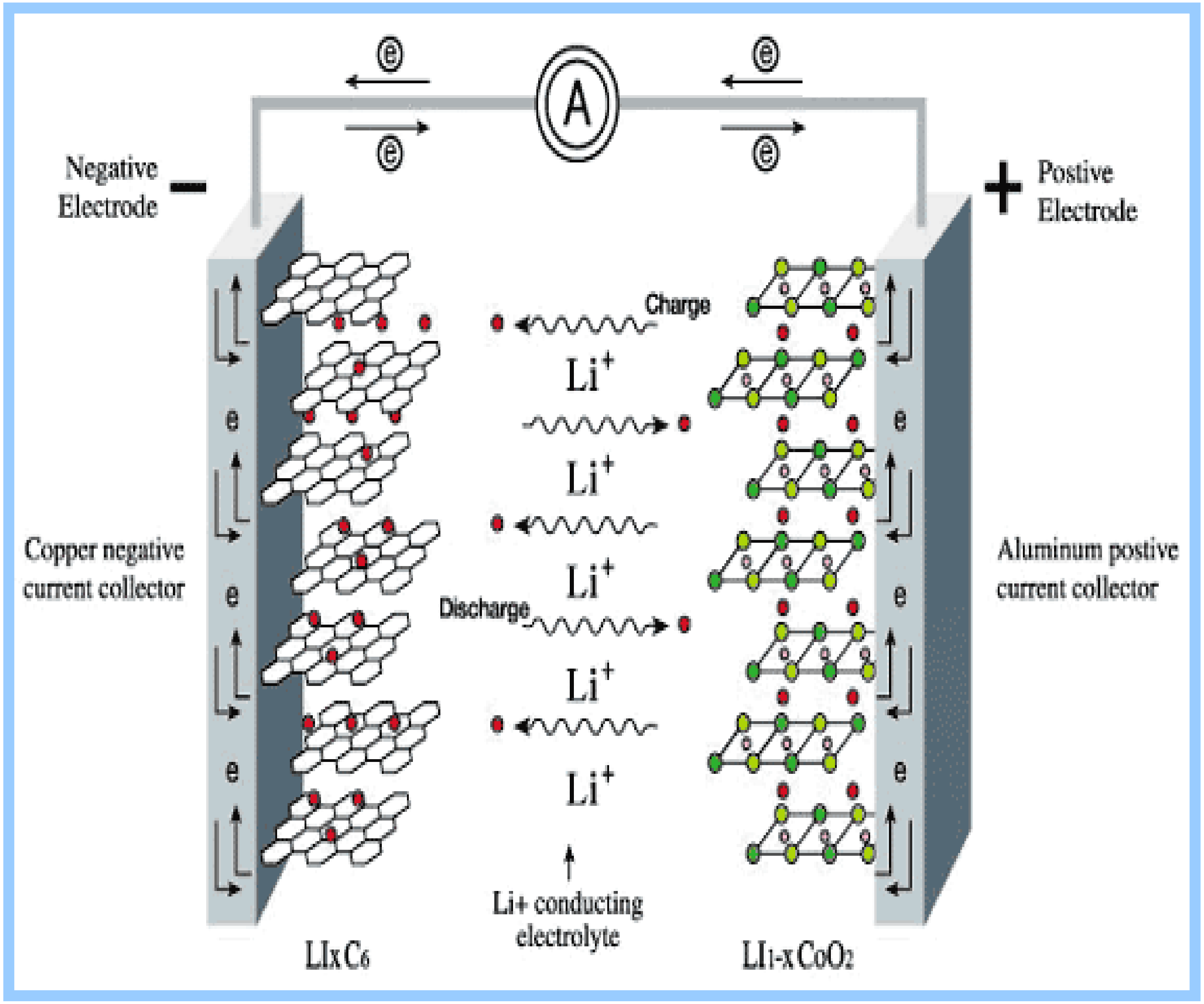


Figure 1.3.1 (*a*) Galvanic and (*b*) electrolytic cells.

A.J. Bard, L. R. Faulkner, Electrochemical Methods, Wiley, 2001.

리튬이차전지



$$LiCoO_2 + C_6 \underset{\text{방전}}{\overset{\text{충전}}{\leftrightarrow}} Li_{1-x}CoO_2 + Li_xC_6$$

2019년 노벨화학상

리튬이차전지

존 굿이너프

John B. Goodenough

스탠리 휘팅햄

M. Stanley Whittingham

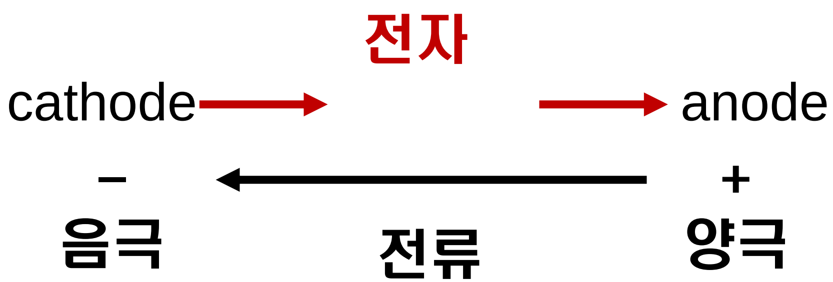
아키라 요시노

Akira Yoshino

Positive electrode(+) and negative electrode(-)

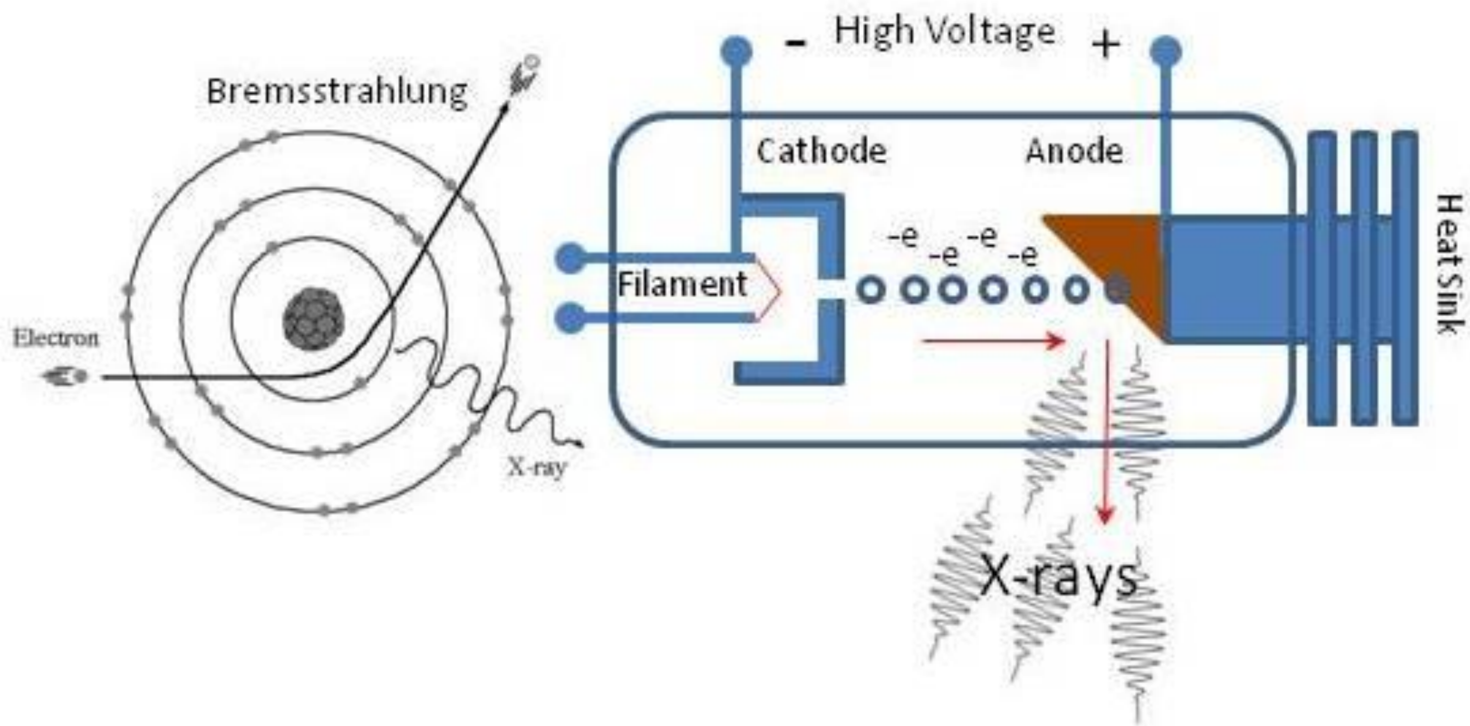
양극, 음극, 산화극(anode), 환원극(cathode)

1834 William Whewell**이 확정** (+Faraday**의 조언**)
-cathode(**그리스어** kathodos(descent, way down**의 뜻**): current exits/emits (to electric device or chemical reaction)



✓**참고**: **데이비**(Humphrey Davy, 1778-1829): **물의 전기분해시 산소발생 전극을 양극**(positive), **수소발생 전극을 음극**(negative)**으로 제안** → **양의 전하를 띤 수소이온이 음극으로 이동**

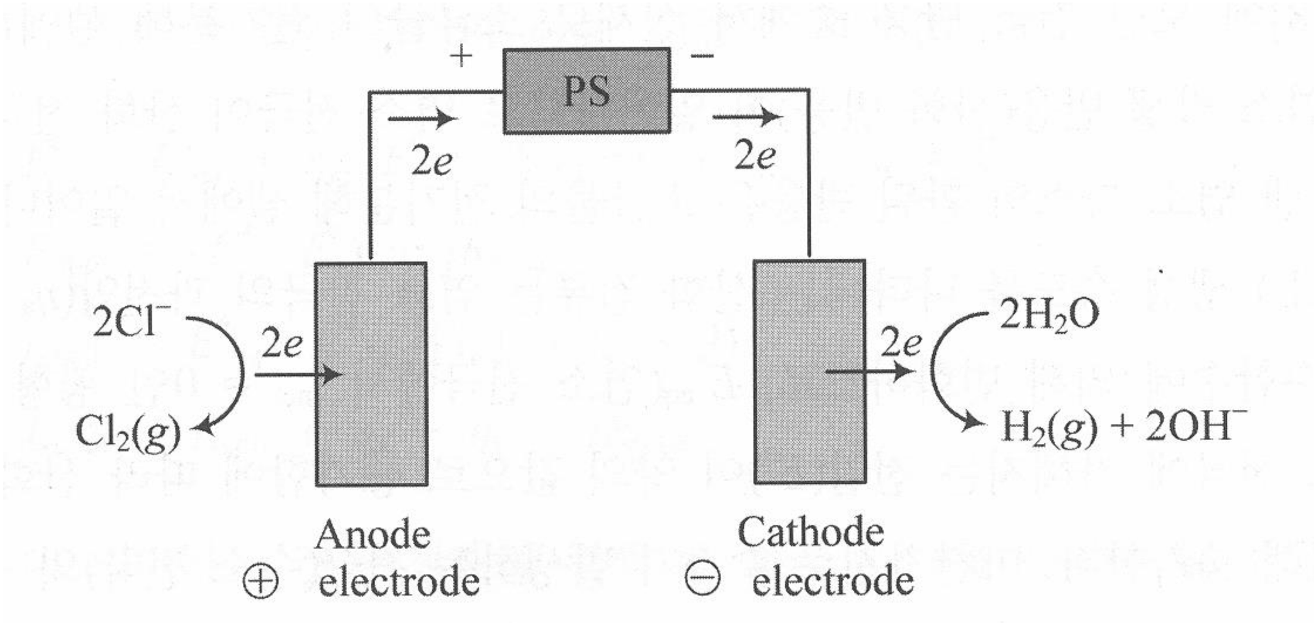
양극, 음극, anode, cathode



http://www.hardhack.org.au/xraydtt

Electrolytic cell: **양극**, **음극**, anode, cathode

✓**바닷물**(NaCl)**의 전기분해**



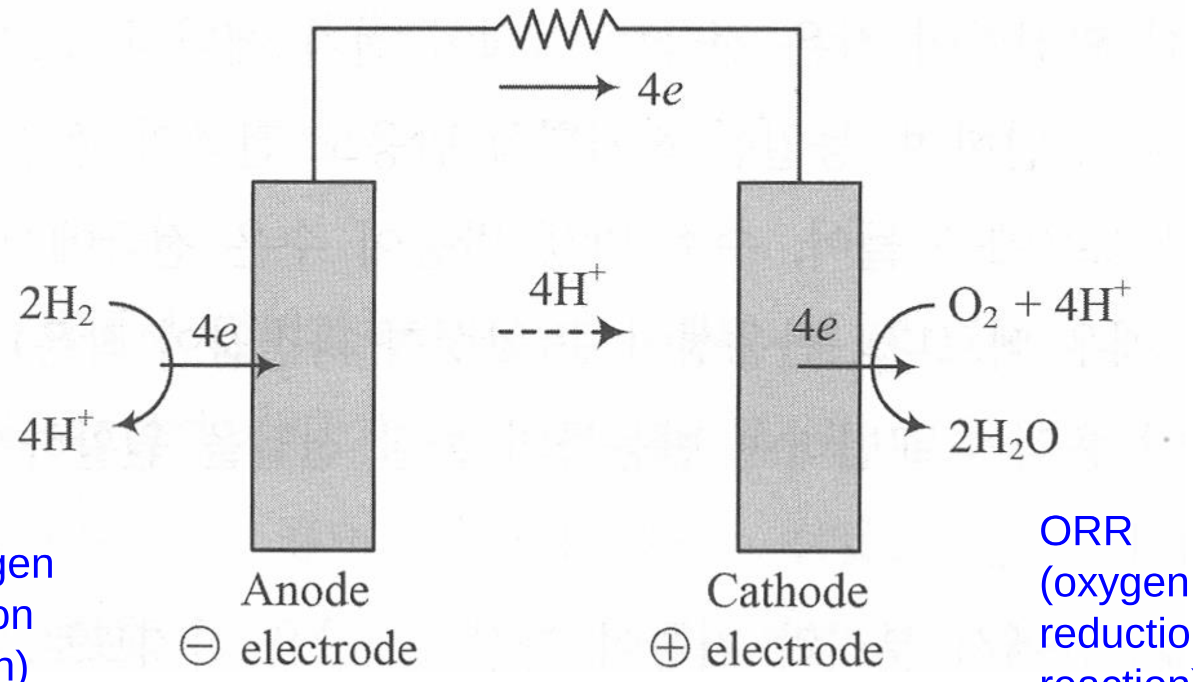
✓**물의 전기분해**:

- **산소발생 전극**(OER(oxygen evolution reaction), anode, **산화**) **양극**(positive)
- **수소발생 전극**(HER(hydrogen), cathode, **환원**) **음극**(negative)

Oh, ch.1

Galvanic cell: **양극**, **음극**, anode, cathode

✓**연료전지**



HOR (hydrogen oxidation reaction)

ORR (oxygen reduction reaction)

Oh, ch.1

2차전지: galvanic cell + electrolytic cell

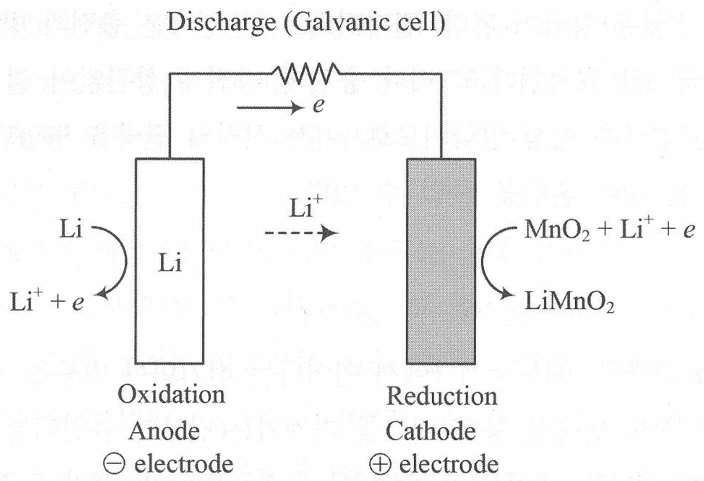


그림 1-21 Li/MnO_2 이차 전지의 방전 과정에서 전극 반응과 전극의 명칭

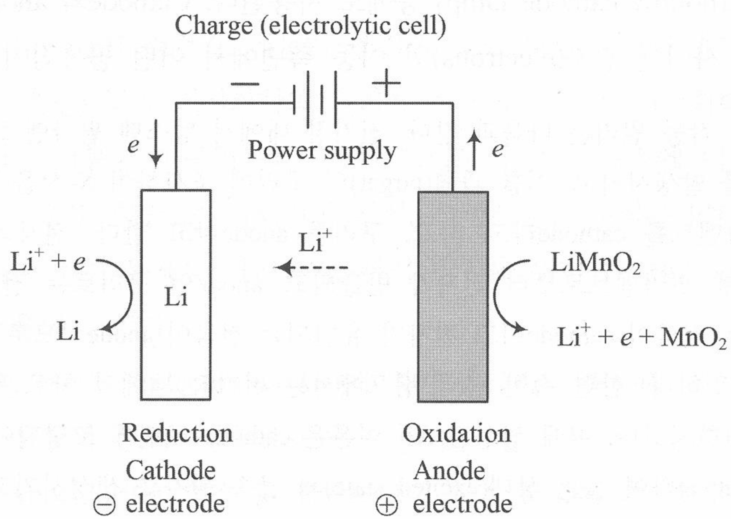


그림 1-22 Li/MnO_2 이차 전지의 충전 과정에서 전극 반응과 전극의 명칭

Oh, ch.1

양극, 음극, 산화극(anode), 환원극(cathode)

Anode	Cathode
The anode is the electrode where el ectricity moves into.	The cathode is the electrode where electricity is given out or flows out of.
A anode is usually the positive side.	A cathode is a negative side.
It acts as an electron donor.	It acts as an electron acceptor.
In an electrolytic cell, oxidation reaction takes place at the anode.	In an electrolytic cell, a reduction reaction takes place at the cathode.
In galvanic cells, an anode can become a cathode.	In galvanic cells, a cathode can become an anode.

https://byjus.com/chemistry/cathode-and-anode/

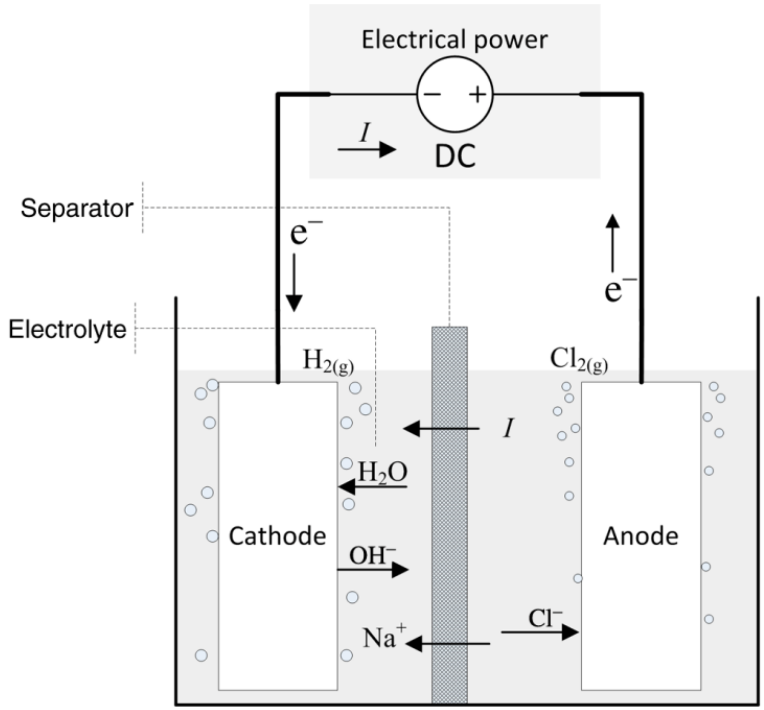


Figure 1.4 Electrochemical cell for the chlor-alkali process.

Chloro-alkali process

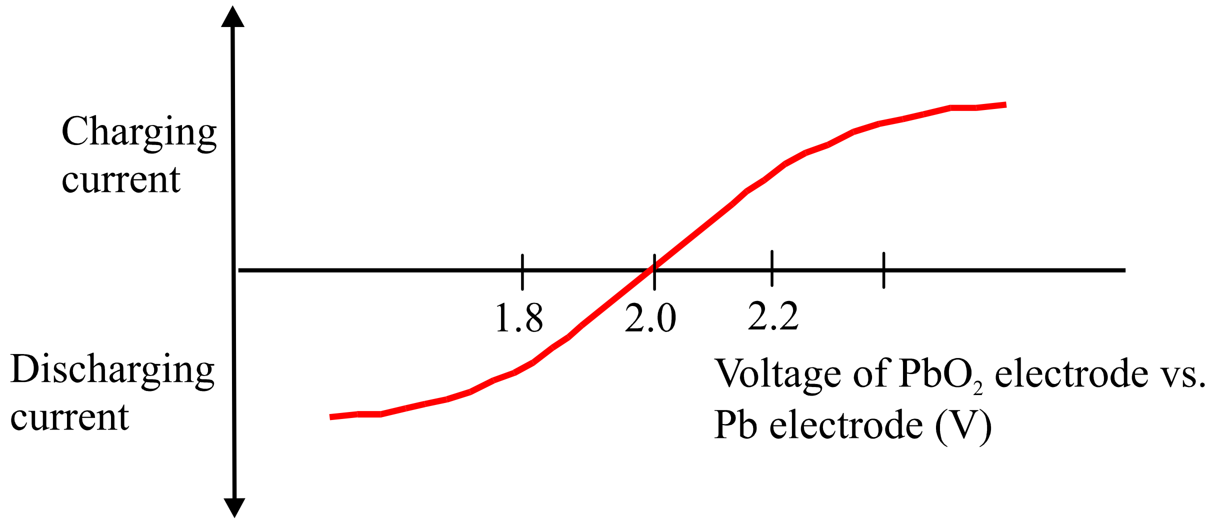
Anode: $2Cl^- \rightarrow 2e^- + Cl_2$

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Overall: $2H_2O + 2Cl^- \rightarrow Cl_2 + H_2 + 2OH^-$

Voltammetry: I-V 관계

Plot of cell currents versus the cell voltages (volt + am(pere) + mogram)



Not linear → electrochemical cells do not obey Ohm's law

Overpotential (or overvoltage, polarization) $\eta = E - E_{eq}$

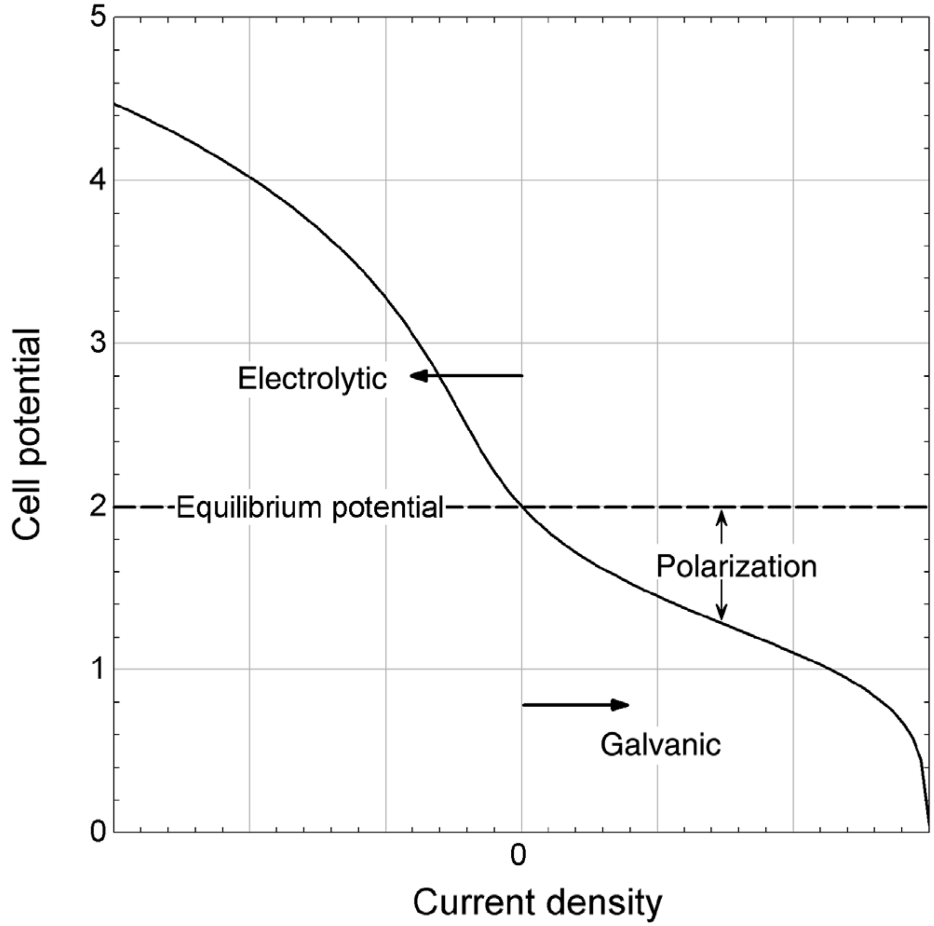


Figure 1.5 Representative relationship between current and potential at steady state. The dividing line between galvanic and electrolytic operation is at a current density of zero.

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering