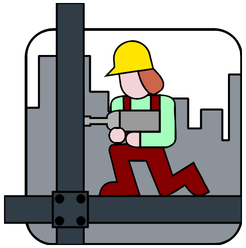
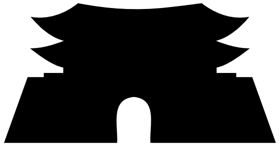
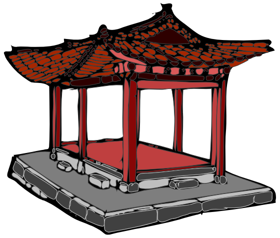
Components of Organic Chemistry



Reactions: synthesis



Organic compounds



Structure

bonding, conformation,

analysis, stereochem.

Reactivity

interaction with other molecules: mechanism, dynamic stereochem.

공부하는 방법

“그저 익숙하도록 읽는 것뿐이다. 글을 읽는 사람이, 비록 글의 뜻은 알았으나, 만약 익숙하지 못하면 읽자마자 곧 잊어버리게 되어, 마음에 간직할 수 없을 것은 틀림없다.

이미 읽고 난 뒤에, 또 거기에 자세하고 익숙해질 공부를 더한 뒤라야 비로소 마음에 간직할 수 있으며, 또 흐뭇한 맛도 있을 것이다.” - 퇴계 이황 (금장태 著)

Chapter 1. Bonding & Structure

- Valence Bond Theory: hybridization & resonance
  - bonding electron pairs are localized between two atoms
  - simple & effective but over-simplified & many exceptions
- Molecular Orbital Theory: Schrödinger equation
  - bonding electrons are distributed over the entire molecule
  - more accurate & close to the real structure but difficult to calculate & many assumptions in calculation

❖ Valence Bond Theory (I)

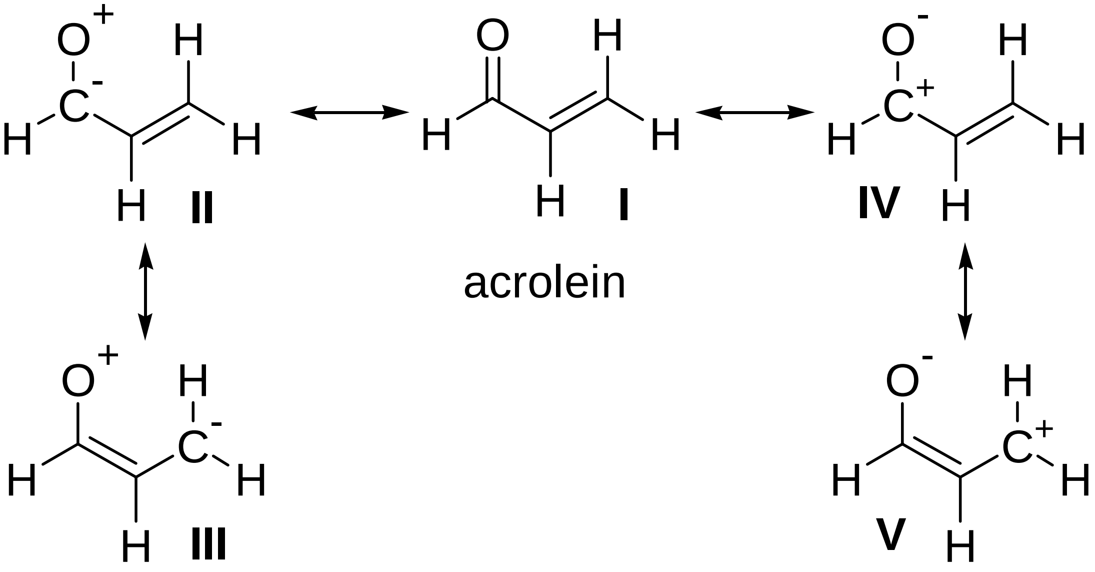
- Lewis in 1916 & Heitler-London in 1927 (H_2: H–H)
    - chemical bonding results from sharing of the electrons between the two atoms: localized bonding electron pairs
- Hybridization: complex molecules (CH_4)
    - directed valence: Pauling in 1931; 📖 4 bot. & 📖 5
        - 4 bonds rather than 2 & more effective overlap due to the highly directional 4 sp^3 orbitals: σ bonds
        - $H_2C=CH_2$ 3 sp^2 & 1 2*p* or 4 sp^3, trigonal; $HC\equiv CH$ 2 *sp* & 2 2*p* or 4 sp^3, digonal: 📖 5 ($H_2C=C=CH_2$?)
            - π bonds from 2 sp^3: bent bonds

Valence Bond Theory (II)

- Hybridization of strained molecules: 3-ring
  - more *p* for C-C (17%, sp^5)& more *s* for C-H (33%, sp^2)
    - bent bonds: less overlap; 📖 7 Fig. 1.5 & 📖 5 Fig. 1.4
    - electronegativity change: more electronegative (*s* character) C in strained molecules; 📖 7 Fig. 1.6
    - propellanes: 📖 8 Fig. 1.7; [4.4.4] sp^3; [2.2.2] sp^2; [1.1.1] inverted carbon – reactive: 📖 8 middle & bottom

❖ Valence Bond Theory (III)

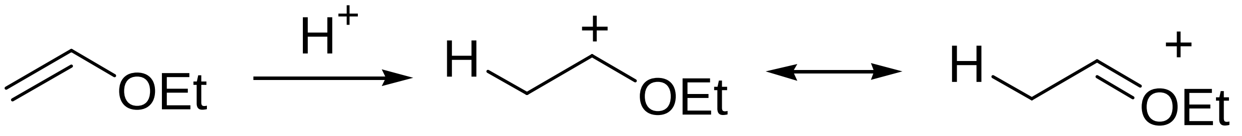
- Resonance theory: more than one Lewis structure possible for complex molecule
  - Rule of thumb: 📖 9 middle (a – d); acrolein



acrolein

❖ Valence Bond Theory (IV)

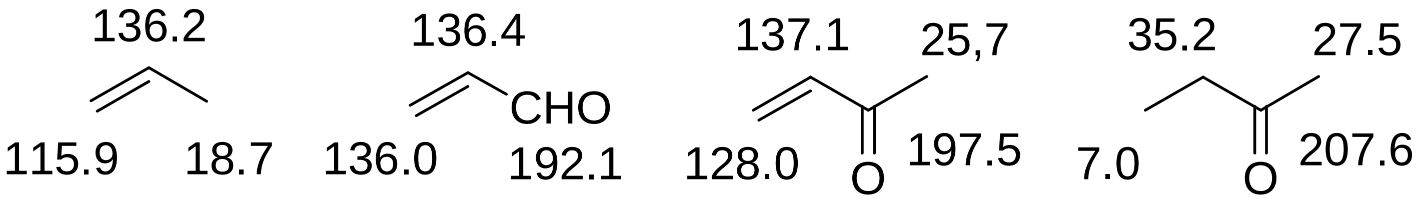
- Application of resonance theory to acrolein
  - a. Acrolein has properties of 5 resonance structures
    - ➢ The real structure is their resonance hybrid
  - b. All resonance structures satisfy the octet rule
  - c. More stable resonance structures resemble more closely the real structure (major contributors): maximum No. of covalent bonds (I), minimum separation of unlike charges (I), negative charge on the more electronegative atom (IV/V)
  - d. Usually, delocalization of electrons enhances stability relatively to a single localized structure: an energy barrier to rotation; 📖 10 top (allyl cation) & 📖 11 top (amide)



more stable

❖ Valence Bond Theory (V)

- Experimental proof for the resonance hybrid
    - the weaker C=O bond: 1690 vs 1730 cm^{-1} (IR)
    - the deshielded β-carbon in ^{1}H & ^{13}C NMR:



- the chemical reactivity: 1,2-/1,4-addition of nucleophiles

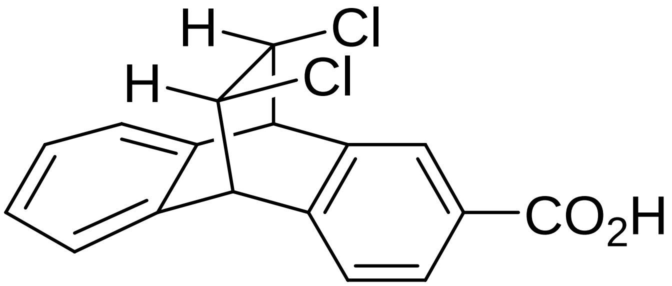
❖ Structural Properties of Chemical Bonds (I)

- Bond length: 🕮 13 Table 1.2
  - nearly constant for a hybridization type of carbon
- Bond energy: variable; 🕮 14 Table 1.3 (homolytic)
  - Heterolytic ΔE_{dis}: more sensitive; 🕮 15 Table 1.4
- Heat of formation: isomers; 🕮 16 Table 1.5
  - stable: branched alkane & more substituted *tans*-alkene
- Polarity: different electronegativity; 🕮 17 Table 1.6
  - dipole moment = Σ bond dipoles; 🕮 17 Table 1.7
  - Mulliken electronegativity (χ) = (I + A) / 2; 🕮 18

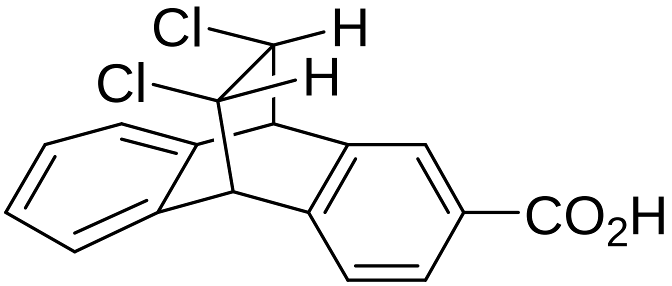
❖ Structural Properties of Chemical Bonds (II)

- Polarity of hydrocarbons: 📖 18 Scheme 1.1
  - electronegativity of C: *sp* > *sp*^{2} > *sp*^{3}; $\overset{\delta^-}{\mathrm{C}}\text{–}\overset{\delta^+}{\mathrm{H}}$ for normal *sp*^{3}
- Polarity transmission: *polar effect*; reactivity
  - inductive effect: successive polarization through bonds
  - field effect: through-space interactions of the electric dipoles
    - substituent effect on reactivity: 📖 19 Table 1.8
- Polarizability: $\propto$ size; 📖 21-23 Table 1.9 & Fig. 1.8
  - response of electrons to nearby charges: HSAB principle
    - hardness: difficult distortion, softness: easy distortion

❖ Field Effect: Through-space Electrostatic Interaction



pK_a = 6.07



pK_a = 5.67

❖ Molecular Orbital (MO) Theory: Overview (I)

- $H\psi = E\psi$: accuracy vs amount of computation
  - LCAO approximation: $\psi = c_1\phi_1 + c_2\phi_2 + \bullet\bullet\bullet\bullet + c_n\phi_n$
  - minimum basis set: combination of AO chosen
    - 2*s*, 2p_x, 2p_y, 2p_z for C, N, O and 1*s* for H
  - semiempirical calculations: use of experimentally determined parameters [EHT, CNDO, MINDO-3, MNDO, AM1, MM2, PM3]; faster, simpler but limited applications
  - *ab initio* calculations: absence of adjustable parameters (fewer assumptions) using SCF [STO-3G, 4-31G, 6-31G]; more reliable, accurate but more complex, time-consuming
  - comparison between the two calculations: 📖 29 Table 1.12

❖ MO Theory: Overview (II)

- ❒ Results obtainable from MO calculations
  - ◆the energy of each MO & charge distributions
  - ◆total electronic energy of the molecule relative to the atoms
    - ❍the calculated molecular energy → relative stabilities of isomeric molecules → conformational effects (the total energy as a function of molecular geometry)
  - ◆the minimum energy: the most favorable molecular structure
  - ◆the coefficients of the AOs contributing each MO
  - ◆applicable to the situation in the gas phase (on a single molecule)

❖ MO Theory: Applications (I)

- Charge distribution of a molecule
  - the electron density (q) at each atom r : CH_3^+; 📖 27 Table 1.10
    - $q_r = \sum_j n_j c_{jr}^2$, n=No. of e^-, c_j=coefficient at jth MO
    - 7 MOs from 3 H 1s & C 2s, 2p_x, 2p_y, 2p_z
    - 3 occupied MOs with 2 e^- for each
    - q_C=3.565 e^-, q_H=0.812 e^-: total charge = (+0.435) [(4-3.565)] + 3(+0.188) [3(1-0.812)] = +1.000
    - LUMO: p_z (localized purely on the carbon atom)
      - *cf.*: 3 sp^2 & 1 p_z from VB theory

❖ MO Theory: Applications (II)

- Heat of reaction: $\Delta H_f = \sum\Delta H_{reactant} - \sum\Delta H_{product}$
  - isodesmic reactions: test of reliability; 🕮 28-9 Table 1.11-12
    - the same No. of formal bonds of each type on each side
- Structure & energy: CH_3^+, CH_3•, CH_3^-; 4-31G basis set
  - Fig. 1.9, 🕮 29: CH_3^+ & CH_3•, planar; CH_3^-, non-planar
- Substituent effects: π-donor vs inductive effects
  - **X**-CH_2^+ vs **H**-CH_2^+ : 🕮 29 middle & 🕮 30 Table 1.13
  - **X**-CH_2^- vs **H**-CH_2^- : 🕮 31 Table 1.14
    - vinyl: rotational barrier of an allyl cation & anion

❖ Hückel Molecular Orbital (HMO) Theory (I)

- Simple but useful for the conjugated compounds
  - assumption: the π-system can be treated independently of the σ framework in conjugated planar molecules (orthogonality) & mainly determines the chemical and spectroscopic properties
- Energy levels for each MO
  - $E=\alpha+m_j\beta$, $m_j=2\cos[j\pi/(n+1)]$: linear polyenes; 📖 32 Table 1.15
    - α: Coulomb integral, a constant for all carbon atoms
    - β: resonance integral, 0 for nuclei of nonbonding distance
  - $DE = \sum E_{\text{polyene}} - \sum E_{\text{ethylene}} = (6\alpha+6.988\beta) - (6\alpha+6\beta) = 0.988\beta$, $\beta \approx 18$ kcal/mol; $[2(\alpha+1.802\beta)+2(\alpha+1.247\beta)+2(\alpha+0.445\beta)]$

❖ Hückel Molecular Orbital (HMO) Theory (II)

- Coefficients of 2*p* AO of atom *r* for each MO: 📖 32 bot.
  - a node between different signs: antibonding; 📖 34 Fig. 1.10
  - bonding between the similar size in concerted reactions
- Hückel's rule: planar monocyclic conjugated polyenes
  - aromatic: [4n+2] e^- in the π system; antiaromatic: [4n] e^-
    - benzene-aromatic vs cyclobutadiene-antiaromatic
  - $E=\alpha+m_j\beta$, $m_j=2cos(2j\pi/n)$: 📖 35 Fig. 1.11 (annulenes)
    - $DE_{benz} = 2\beta$ vs $DE_{cybu} = 0$; (aromatic) vs (antiaromatic)
  - Frost's circle: a mnemonic; 📖 35 Fig. 1.12
- Charged C_3H_3 & C_5H_5 systems: 📖 36 Fig. 1.13

❖ Calculation of Total Electron Energy *E*

- Cyclobutadiene: $E_{\text{cybu}} = 4\alpha + 4\beta$
  - j=0, $m_0 = 2\cos(0/4) = 2$; j =±1, $m_{\pm1} = 2\cos(\pm 2\pi/4) = 0$; j=+2, $m_{+2} = 2\cos(4\pi/4) = -2$; $E_1 = \alpha + 2\beta$, $E_2 = E_3 = \alpha$, $E_4 = \alpha - 2\beta$ (empty)
  - $DE_{\text{cybu}} = \sum E_{\text{cybu}} - \sum E_{\text{ethylene}} = [2(\alpha+2\beta)+1\alpha+1\alpha] - (4\alpha+4\beta) = 0$
- Benzene: $E_{\text{benz}} = 6\alpha + 8\beta$
  - j=0, $m_0 = 2$; j =±1, $m_{\pm1} = 2\cos(\pm 2\pi/6) = 1$; j=±2, $m_{\pm2} = 2\cos(\pm 4\pi/6) = -1$; j=+3, $m_{+3} = 2\cos(+6\pi/6) = -2$; $E_1 = \alpha + 2\beta$, $E_2 = E_3 = \alpha + \beta$, $E_4 = E_5 = \alpha - \beta$ (empty), $E_6 = \alpha - 2\beta$ (empty)
  - $DE_{\text{benz}} = \sum E_{\text{benz}} - \sum E_{\text{ethylene}} = [2(\alpha+2\beta)+4(\alpha+\beta)] - (6\alpha+6\beta) = 2\beta$

❖ MO Energy Level of Acyclic Polyenes

- Allyl cation: $E = 2\alpha + 2.83\beta$; anion: $E = 4\alpha + 2.83\beta$
  - Ψ_1 [$E = \alpha + 1.414\beta$], Ψ_2 [$E = \alpha$], Ψ_3 [$E = \alpha – 1.414\beta$]
- Butadiene: $E = 4\alpha + 4.47\beta$
  - Ψ_1 [$E = \alpha + 1.618\beta$], Ψ_2 [$E = \alpha + 0.618\beta$]
  - Ψ_3 [$E = \alpha - 0.618\beta$], Ψ_4 [$E = \alpha - 1.618\beta$]
- Pentadienyl cation: $E = 4\alpha + 5.46\beta$

  Pentadienyl anion: $E = 6\alpha + 5.46\beta$
  - Ψ_1 [$E = \alpha + 1.732\beta$], Ψ_2 [$E = \alpha + 1.000\beta$], Ψ_3 [$E = \alpha$]
  - Ψ_4 [$E = \alpha - 1.000\beta$], Ψ_5 [$E = \alpha – 1.732\beta$]

❖ Qualitative Application of MO Theory(I)

- Rules for construction of MO energy level diagram
  - total No. of MOs = ∑ No. of AOs; aufbau principle
  - the symmetry of MOs = the symmetry of the molecule
    - symmetric: the same sign, antisymmetric: opposite sign
  - orthogonal orbitals do not interact: p_x, p_y, p_z
  - the energy of more electronegative atoms is lower
  - the more the No. of nodes, the higher the energy
- Diatomic molecules with 1*s* AO: 🕮 37 Fig. 1.14
  - H_2^+, H_2, He_2^+, He_2, HHe^+: 61, 103, 60, (0), 43 kcal/mol

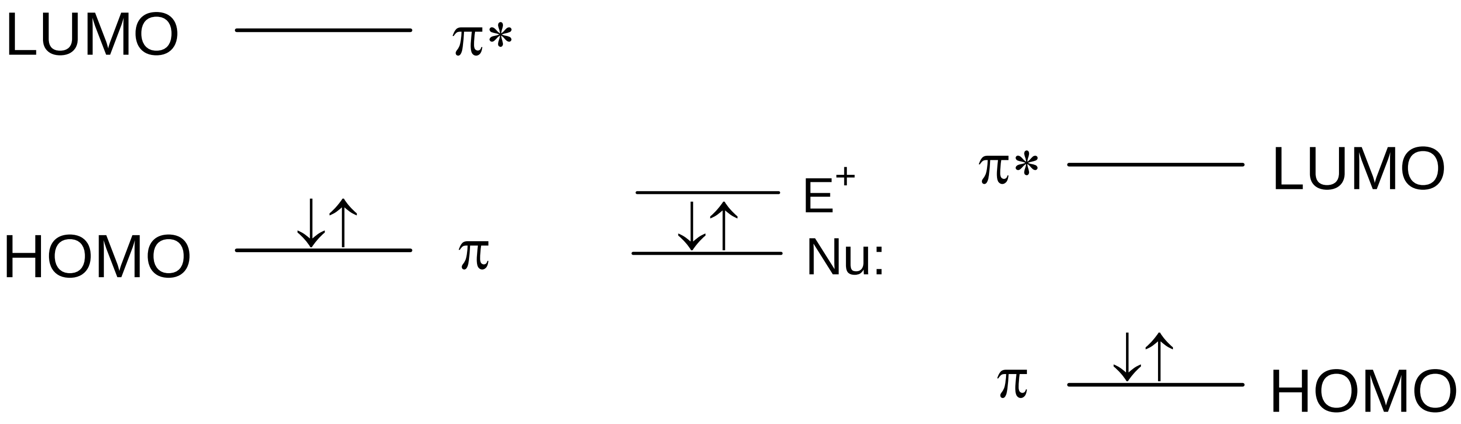
Qualitative Application of MO Theory(II)

- Energy level diagram of CO: 📖 38 Fig. 1.15
  - total No. of MOs = 10 (C & O: 1*s*, 2*s*, $2p_x$, $2p_y$, $2p_z$; 14 e^-)
    - the MOs 1*s* e^-: negligible due to the large energy gap
    - 10 e^- in 5 MOs from 8 MOs: 4 bonding & 1 antibonding
- MO energy diagram of CH_4: 📖 40 Fig. 1.18
  - *ab initio* calculation results: no 4 equivalent MOs
  - qualitative analysis of energy diagram
    - frame of reference: a cube; 📖 37 Fig. 1.14
    - 3 C_2 axes (x, y, z): symmetrical or antisymmetrical

❖ Application of MO Theory to Reactivity (I)

- ❒ Perturbation MO (PMO) theory for new MOs
  - ◆ change of the MO pattern with a change in structure
    - ❍ the changes are small & the new MO pattern would be similar to known MOs of the similar system
  - ◆ strongest interactions between MOs with close energy
    - ❍ FMO theory: important interactions between HOMO of one reactant & LUMO of the other; relative energy
  - ◆ only MOs of matching symmetry can interact
- ❒ Reactivity difference between $CH_2{=}CH_2$ & $CH_2{=}O$
  - ◆ ethylene with E^+ & formaldehyde with Nu: 📖 48 Fig. 1.25

❖ Reactivity Difference: $CH_2{=}CH_2$ & $CH_2{=}O$



LUMO π*

HOMO π

E^+

Nu:

π* LUMO

π HOMO

$H_2C{=}CH_2$

$H_2C{=}O$

❖ Application of MO Theory to Reactivity (II)

- Substituent effects on the reactivity of double bonds
  - ethylene with a π-donor: reactive to E^+; 📖 49 top figure
    - allyl anion: reactive site at the terminal atoms; β-C & N
  - ethylene with a π-acceptor: reactive to Nu; 📖 49 middle
    - butadiene: larger coefficient at the β-C of LUMO
  - prediction with VB theory: resonance; 📖 49 bottom
- Concerted reactions & symmetry: 📖 53 bottom
  - allyl cation & ethylene: forbidden; 📖 51 Fig. 1.27
  - allyl cation & butadiene: allowed; 📖 52 Fig. 1.28

❖ Application of MO Theory to Reactivity (III)

- ❒ Hyperconjugation of allylic systems
  - ◆ interaction between σ & π bonds: σ bonds not on the nodal plane of π-system; 📖 54 middle
  - ◆ eclipsed conformation favored: 1.5-2.0 kcal/mol
    - ❍ repulsive & attractive interactions: 📖 55 top & Fig. 1.30
    - ❍ slightly longer C_3-H & C_1=C_2 but shorter C_3-C_2
  - ◆ prediction with VB theory: ‘no-bond’ resonance; 📖 55
- ❒ Rotational barrier: 3 kcal/mol, ethane; 📖 55 middle
  - ◆ hindered rotation due to π character of some MOs: 📖 56 Fig. 1.31

❖ Other Quantitative Methods

- ❐ Molecular graphs & critical points: 📖 58 Fig. 1.32
    - ◆ Partial structures from MO quantitative calculations
        - ❍ partition of total electron density among atoms
    - ◆ applications: 📖 59-62 Table 1.17 & Figs. 1.33-5
- ❐ Density functional theory (DFT): the B3LYP method
    - ◆ simpler calculation & rather accurate: 📖 63 Tables 1.18-9
    - ◆ electronegativity: $V = n / r$: 📖 61 top & 64 Table 1.20
        - ❍ n: No. of valence-shell e^-, r : effective atomic radius
    - ◆ hardness & V: acidity & stability; 📖 64 & 22 Table 1.21 & 9
- ❐ Quantitative VBT: localized MOs & delocalization