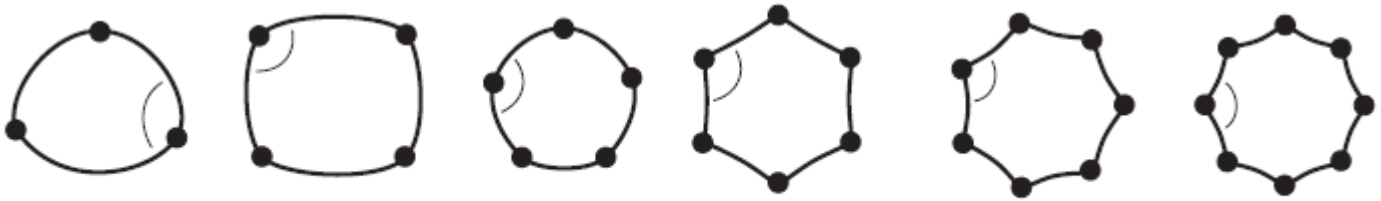
Leibniz Universität Hannover

Strained organic molecules

Group Seminar 19.11.12
Steffen Friedrich



J.F. Liebman, A. Greenberg, *Chem.Rev.* **1976**, *76* (3), 311.
A. De Meijere, *Chem. Rev.* **2003**, 103, 931.

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The concept of strain

How can one compare the relative stabilities of organic compounds?

Thermodynamic stability is determined by free energy (ΔG):

Gibb‘s equation: $\Delta G = \Delta H - T\Delta S = -RT \ln K_p$

dominant term at **low** to **ambient temperatures**!

- bonding energy
- nonbonding interactions
- **strain**…etc.

dominant term at **high temperatures**!

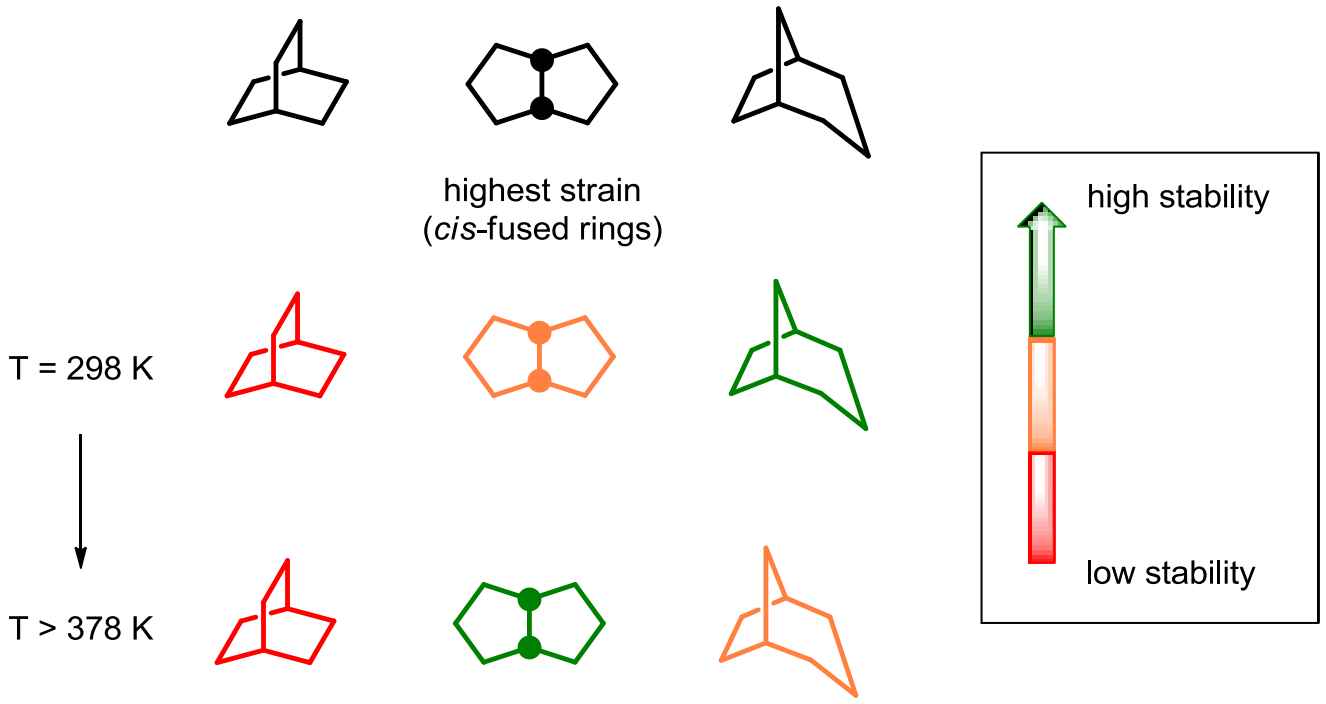
- molecule symmetry
- conformational freedom

The concept of strain

The less strained isomer isn‘t always the most stable one!

$$\Delta G = \Delta H - T\Delta S = -RT \ln K_p$$

Bicyclooctanes



The concept of strain

⟹ heat of formation ΔH_f^0 (calorimetry):

	benzene	cyclopropane
ΔH_f^0	+19.8 kcal/mol	+12.7 kcal/mol

cyclopropane is more stable (less strained) than benzene? …

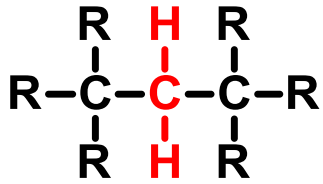
No! This definition of stability must be limited to a set of isomers!

The concept of strain

… a possible solution: compare **bond energies** or **group increments**

compound	ΔH_f^0 (gas, 25 ° C), kcal/mol	Increment, kcal/mol
ethane	-20.24	
propane	-24.83	-4.59
n-butane	-30.36	-5.53
n-pentane	-35.10	-4.74
n-hexane	-39.92	-4.82
n-heptane	-44.85	-4.93
n-octane	-49.86	-5.01
n-nonane	-54.66	-4.80
n-decane	-59.62	-4.96

Average ΔH_f^0 -4.95 kcal/mol for one



Quantification of ring strain

- Benson group increment theory:

  „The difference in energy between the actual heat of formation of the cyclic compound and the sum of the appropriate group equivalents is the conventional ring strain energy.“

CRSE = ΔH_f^0 - 3*GE = 12.74 – 3*(-4.95) = 27.69 kcal/mol

CRSE = ΔH_f^0 - 4*GE = 12.74 – 3*(-4.95) = 26.59 kcal/mol

- not suitable for computational approaches

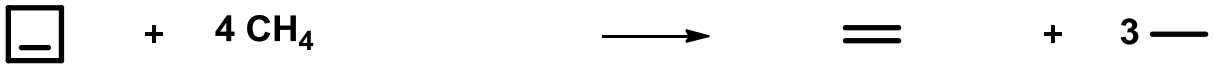
Quantification of ring strain

- Reference approach:
  - Idea: set up a balanced chemical reaction, where the educt is a strained molecule and the product is an unstrained reference

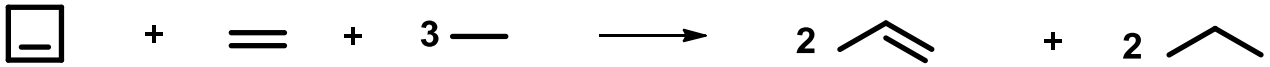
⟹ calculate the energy of all species and the overall reaction energy

⟹ RSE

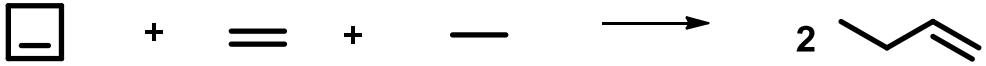
isodesmic



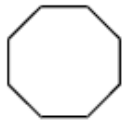
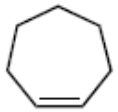
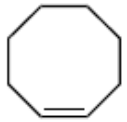
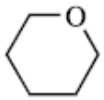
homodesmotic



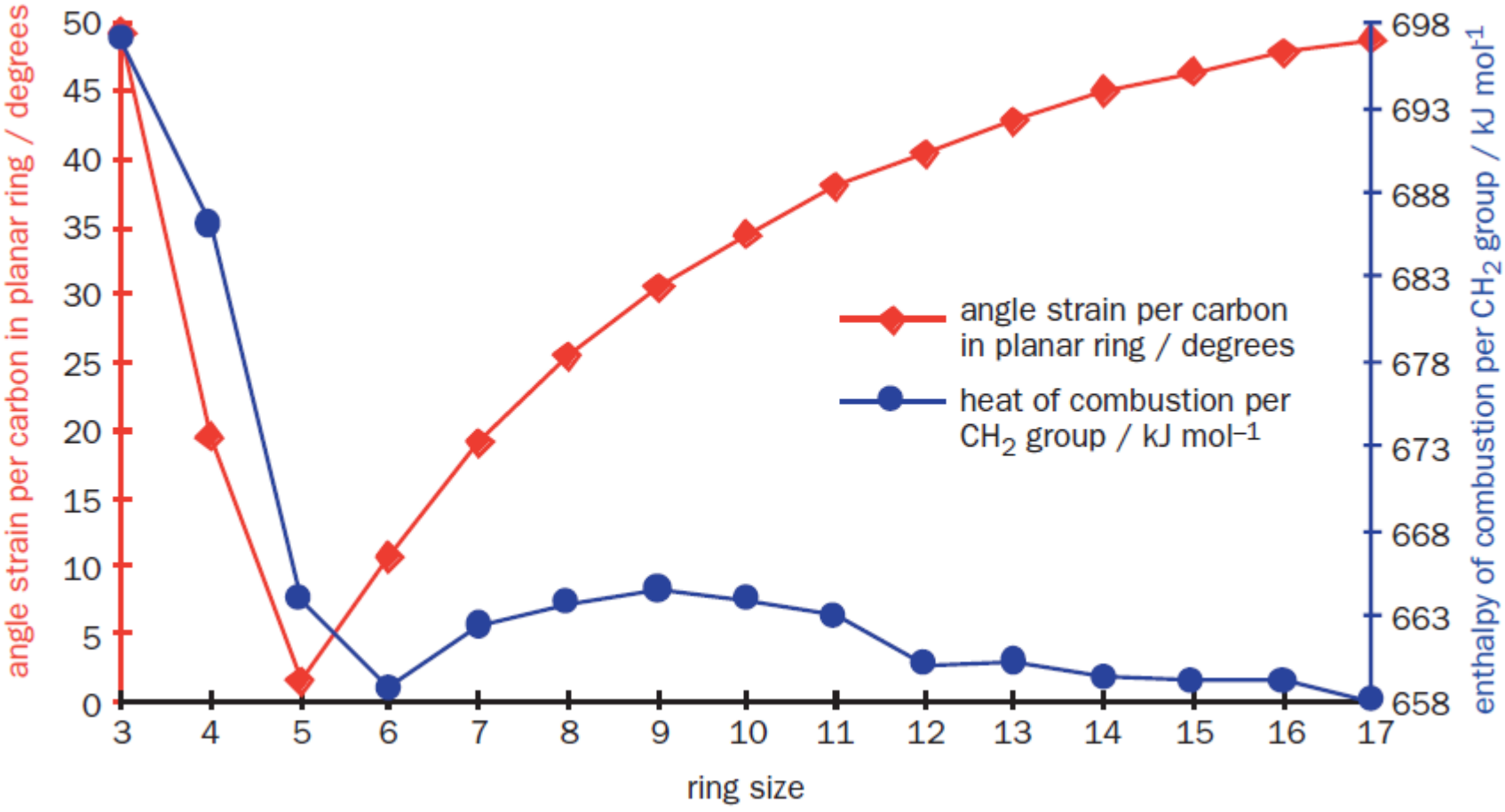
group equivalent



Quantification of ring strain

Method	 **23**	 **24**				
Isodesmic	19.48	15.77	−7.03	−16.01	−12.50	−11.76
Homodesmotic	27.72	26.77	6.72	0.48	6.74	10.23
Group equiv.	**28.03**	**26.34**	**6.54**	**0.51**	**6.69**	**11.70**
CRSE[b]	27.6	26.2	6.3	0	6.4	9.9
		 **25**				
Isodesmic	40.39	13.86	−13.24	−20.29	−19.05	−21.06
Homodesmotic	54.18	30.40	6.05	1.74	5.74	6.48
Group equiv.	53.54	29.92	5.57	1.27	5.26	6.00
	55.01	**31.20**	**6.09**	**1.39**	**5.78**	
CRSE[b]	53.7	29.8	5.9	1.4	5.4	6.0
		 **26**				
Isodesmic	10.42	6.00	−16.54	−23.66		
Homodesmotic	21.39	19.72	−0.07	−4.45		
Group equiv.[c]	27.51	25.84	6.05	1.67		
	27.11	**25.59**	**6.25**	**1.47**		
Group equiv.[d]	27.65	25.98	6.19	1.82		
	27.52	**26.00**	**6.65**	**1.87**		
CRSE[b]	27.6	26.4	6.7	2.2		

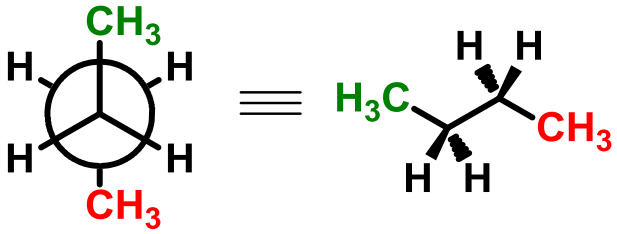
Strained cyclic molecules - Carbocycles



Structure and reactivity of some strained molecules

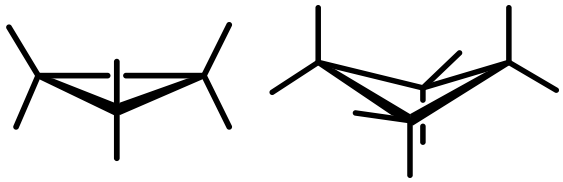
What is the origin of molecular strain?

- Torsional distortion (PITZER strain)
  - deviation from zig-zag alkylchain

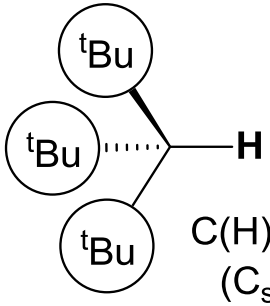


staggered, antiperiplanar

- Bond angle distortion (BAEYER strain)
  - deviation from 109,5° (sp^3), 120° (sp^2)



- Linear bond stretching or compression (VAN DER WAALS strain)

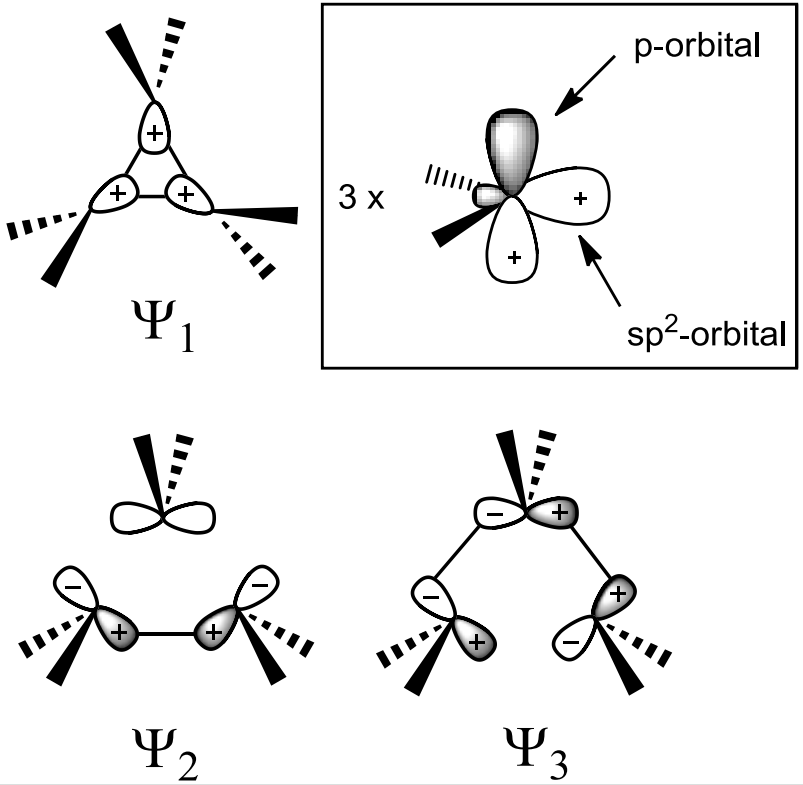


C(H)-C(^{t}Bu) = 1.61 A
(C_{sp3}-C_{sp3} = 1.54 A)

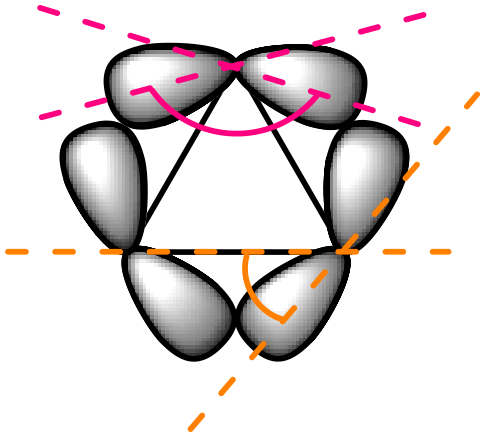
Cyclopropane

- **1876** - VIKTOR MEYER doubts that they can exist at all
- **1882-84** - AUGUST FREUND and WILLIAM HENRY PERKIN synthesize the first cyclopropanes
- **1885** - ADOLF VON BAEYER rationalizes the enhanced reactivity of cyclopropanes on the basis of their inherent ring strain

Walsh orbitals: sp^2-hybridisation



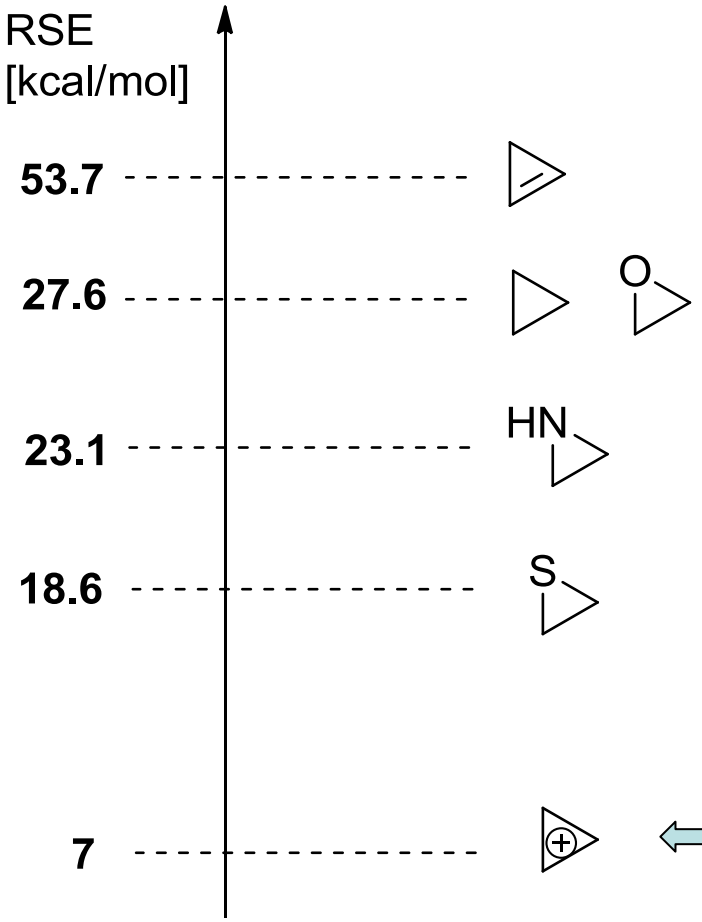
Bent Bonds: sp^3-hybridisation



interorbital angle α: 104°
bending angle β: 21°

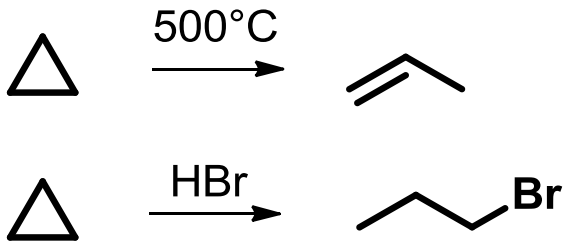
(COULSON-MOFFITT model)

Cyclopropane

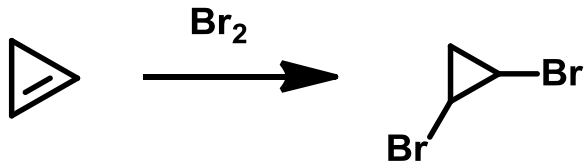


aromaticity

Cyclopropane reacts like an olefin:

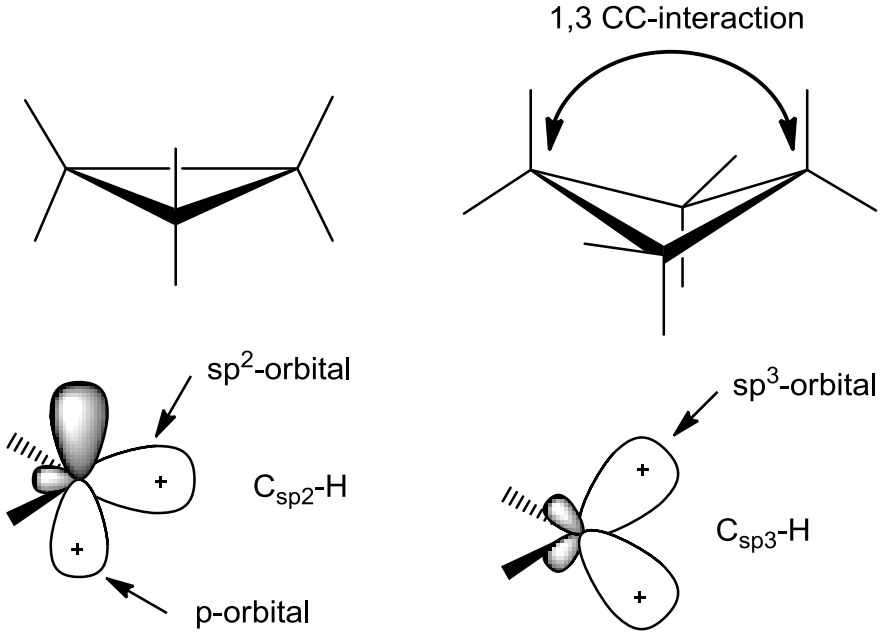


Cyclopropene reacts violently to form cyclopropane derivatives:



Cyclopropane

- Why have cyclopropane and cyclobutane almost identical RSE?
  - Stereoelectronic effects that stabilize cyclopropane:



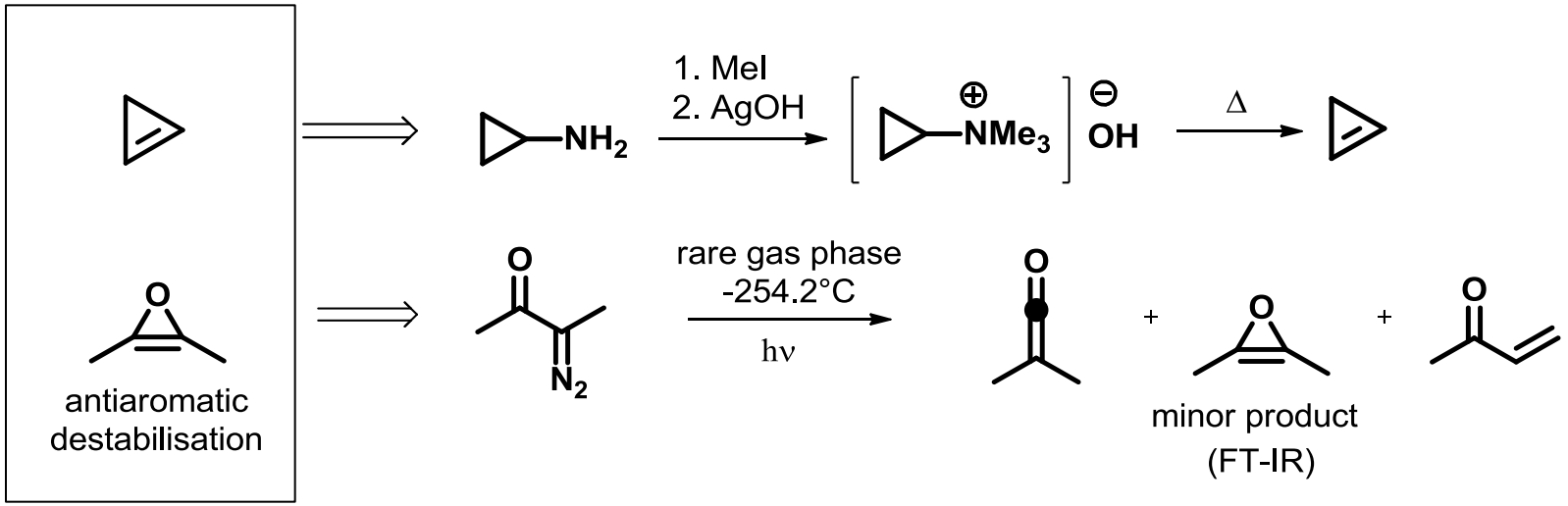
- no nonbonding 1,3 CC repulsion (Dunitz-Shomaker-strain)

- stronger (shorter) C-H-bonds due to higher s-character

Cyclopropane gains
~ 11 kcal/mol stabilisation energy

Cyclopropene

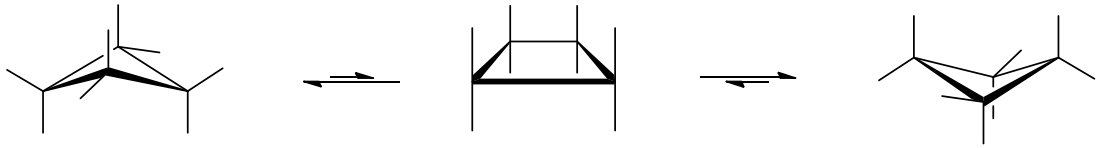
- Ideal C_{sp2}-C(X) bond angles (120°) deviate even more from internuclear bond angles (60°)
- Cyclopropene is one of the most unstable compounds ever isolated



Cyclobutanes and Cyclopentanes

Conformations determined by Pitzer-strain:

~ 1 kcal/mol
inversion barrier



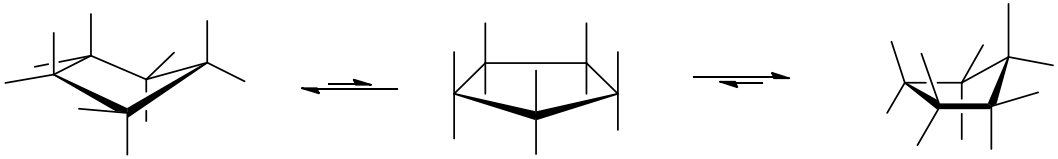
puckered 'wing' conformation

- more staggered C-H-bonds

planar cyclobutane

- 90° C-C bond angel
- eclipsing C-H-bonds cause 1,2 and 1,3 nonbonded repulsion

puckered 'wing' conformation



'envelope' conformation

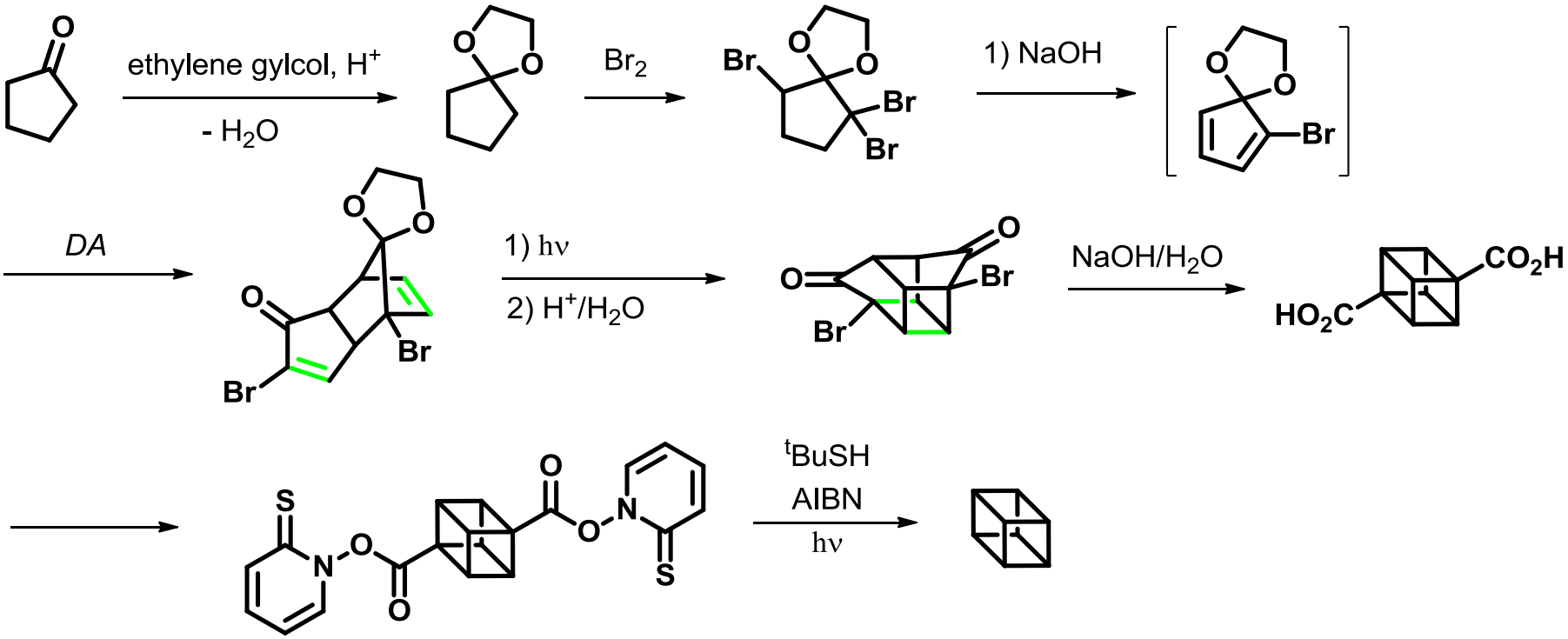
planar cyclopentane

- 108° C-C bond angel
- eclipsing C-H-bonds cause 1,2 and 1,3 nonbonded repulsion

'envelope' conformation

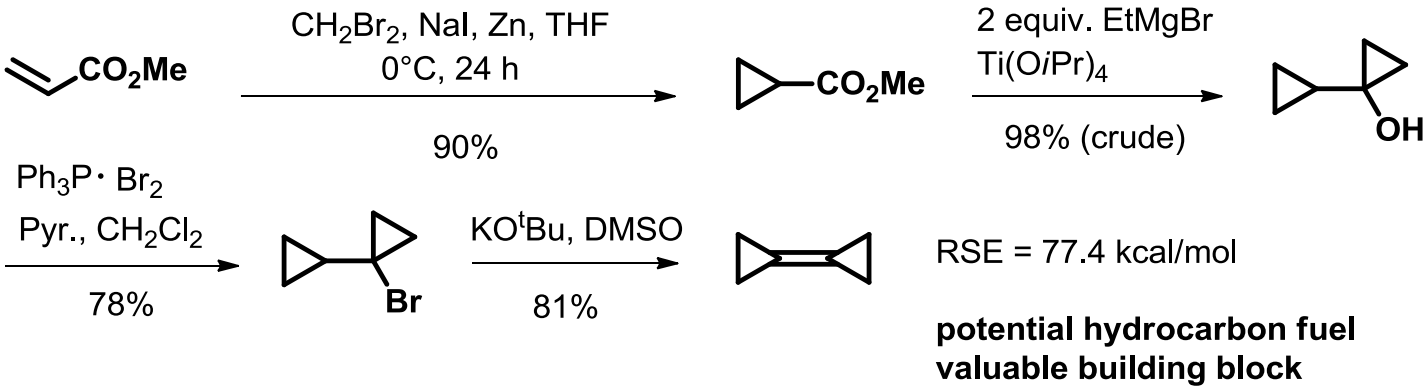
Synthesis of strained molecules I:

Cubane



Synthesis of strained molecules II:

Dicyclopropylidene



RSE = 77.4 kcal/mol

potential hydrocarbon fuel
valuable building block