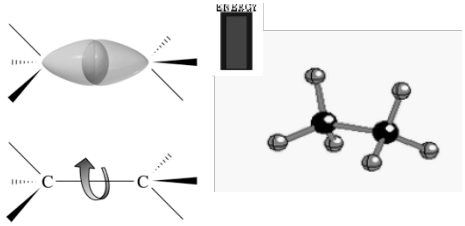
**Chapter 4**

**Alkanes & Cycloalkane**

**Conformations**

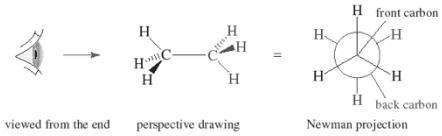
## Conformations of Alkanes: Rotation about Carbon–Carbon Bonds



## Conformational Analysis

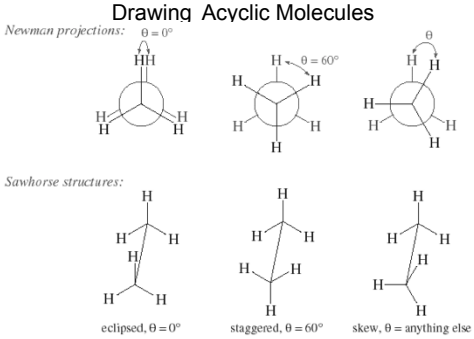
Drawing Acyclic Molecules

- Newman Projections



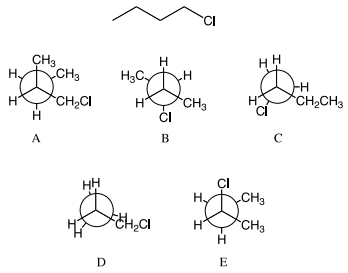

## Conformational Analysis

Drawing Acyclic Molecules

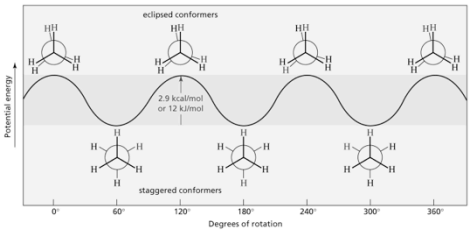



## Question

Which of the following is a Newman projection of the following structure?



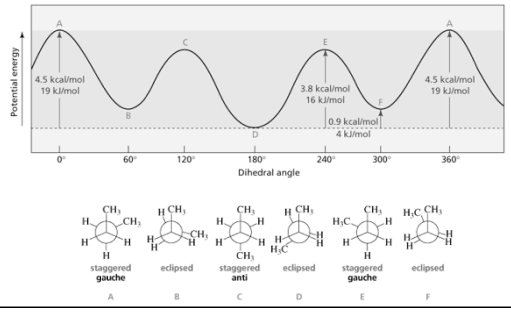

## Different Conformations of Ethane




- A staggered conformer is more stable than an eclipsed conformer
- Torsional strain: repulsion between pairs of bonding electrons

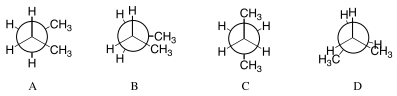
## Conformations of *n*-Butane

- Steric strain: repulsion between the electron clouds of atoms or groups



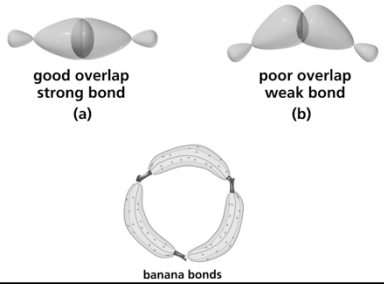

## Question

Which of the following is the lowest in energy?




## Cycloalkanes: Ring Strain

- Angle strain results when bond angles deviate from the ideal 109.5° bond angle




## *The Shapes of Cycloalkanes: Planar or Nonplanar?*

## Adolf von Baeyer (19th century)

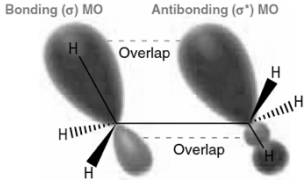
- **Assumed cycloalkanes were planar polygons.**
- **Believed distortion of bond angles from 109.5° gives angle strain to some cycloalkanes.**
- **One for two is great in baseball.**

## Types of Strain

- *Torsional strain*
  strain that results from eclipsed bonds (measure of the dihedral angle)
- Van der Waals strain or (*Steric strain*)
  strain that results from atoms being too close together.
- *Angle strain* results from distortion of bond angles from normal values, for a tetrahedron 109.5°

## TORSIONAL STRAIN

- Can be explained using VSEPR theory or molecular orbital theory.
- In the favored staggered conformation, the bonding and antibonding MOs of neighboring carbons overlap but atoms do not overlap.




## Measuring Strain in Cycloalkanes

•Heats of combustion can be used to compare stabilities of isomers.

•But cyclopropane, cyclobutane, etc. are not isomers.

•All heats of combustion increase as the number of carbon atoms increase.

## Measuring Strain in Cycloalkanes

•Therefore, divide heats of combustion by number of carbons and compare heats of combustion on a "per $CH_2$ group" basis.

## Heats of Combustion in Cycloalkanes

| •Cycloalkane | kJ/mol | Per $CH_2$ |
|---|---|---|
| •Cyclopropane | 2,091 | 697 |
| •Cyclobutane | 2,721 | 681 |
| •Cyclopentane | 3,291 | 658 |
| •Cyclohexane | 3,920 | 653 |
| •Cycloheptane | 4,599 | 657 |
| •Cyclooctane | 5,267 | 658 |
| •Cyclononane | 5,933 | 659 |
| •Cyclodecane | 6,587 | 659 |

## Heats of Combustion in Cycloalkanes

| •Cycloalkane | kJ/mol | Per $CH_2$ |
|---|---|---|

•According to Baeyer, cyclopentane should

•have less angle strain than cyclohexane.

| | | |
|---|---|---|
| •Cyclopentane | 3,291 | 658 |
| •Cyclohexane | 3,920 | 653 |

•The heat of combustion per $CH_2$ group is

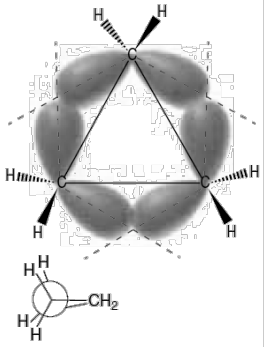
•less for cyclohexane than for cyclopentane.

•Therefore, cyclohexane has less strain than

•cyclopentane.

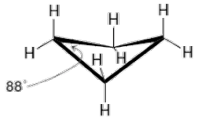
## Cyclic Alkanes – Cyclopropane

- Cyclopropane is 44 kJ/mol less stable than cyclohexane per $CH_2$ group. It is highly strained and very reactive due to:
  1. Angle strain:
     - Bond angles of 60° cause electron pair repulsion in adjacent bonds
     - Inefficient sigma bond overlap
  2. Torsional strain:
     - Eclipsing C–H bonds all the way around the ring—see Newman projection



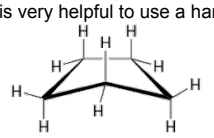
## Cyclic Alkanes – Cyclobutane

- Cyclobutane is 27 kJ/mol less stable than cyclohexane per $CH_2$ group. It is also strained and reactive:
  1. Angle strain results from bond angles of 88°, although it is not as severe as the 60° angles in cyclopropane.
  2. Slight torsional strain results because adjacent C–H bonds are neither fully eclipsed nor fully staggered.




## Cyclic Alkanes – Cyclopentane

- Cyclopentane is only 5 kJ/mol less stable than cyclohexane per $CH_2$ group:
  1. Angles are close to the optimal value.
  2. Identify the minimal but significant torsional strain in the structure. It is very helpful to use a handheld model.



## *Conformations of Cyclohexane*

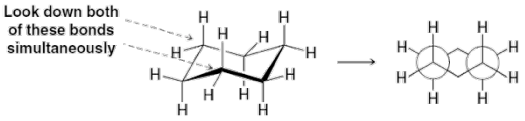
•Heat of combustion suggests that angle strain is unimportant in cyclohexane.

•Tetrahedral bond angles require nonplanar geometries.

• The chair and boat conformations.

## Cyclic Alkanes – Cyclohexane

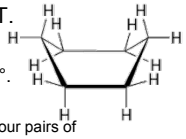
- Cyclohexane is considered to have ZERO ring strain in its optimal conformation, the CHAIR:



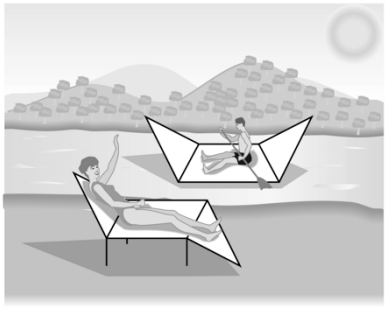

  1. No angle strain—angles must be 109.5°.
  2. No torsional strain—all adjacent C–H bonds must be staggered.

## Cyclic Alkanes – Cyclohexane

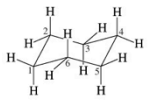
- Other conformations of hexane exist but are a bit less stable. Consider THE BOAT.



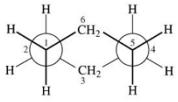
  1. No angle strain—angles are 109.5°.
  2. Torsional strain:
     - Use a molecular model to identify all four pairs of eclipsing C–H bonds
     - Draw a Newman projection that illustrates the torsional strain
  3. Steric strain—flagpole interactions. WHERE?



• The chair conformation of cyclohexane is free of strain



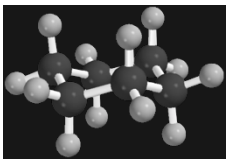
chair conformer of cyclohexane

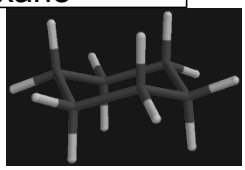


Newman projection of the chair conformer

ball-and-stick model of the chair conformer of cyclohexane

## Chair is the most stable conformation of cyclohexane

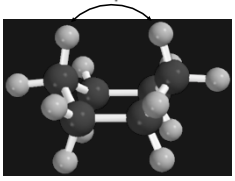


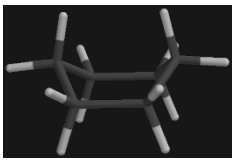


- All of the bonds are staggered and the bond angles at carbon are close to tetrahedral.

## Boat conformation is less stable than the chair

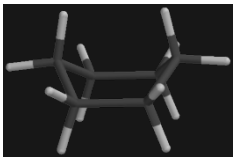
180 pm

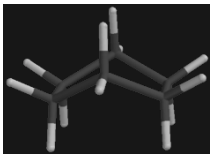




- All of the bond angles are close to tetrahedral but close contact between flagpole hydrogens causes strain in boat.

## Boat conformation is less stable than the chair

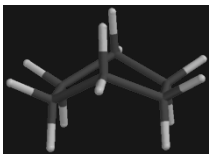




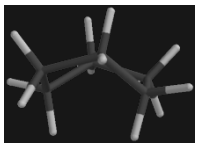
- Eclipsed bonds bonds gives torsional strain to boat.

## Skew boat is slightly more stable than boat

Boat



Skew or Twist Boat



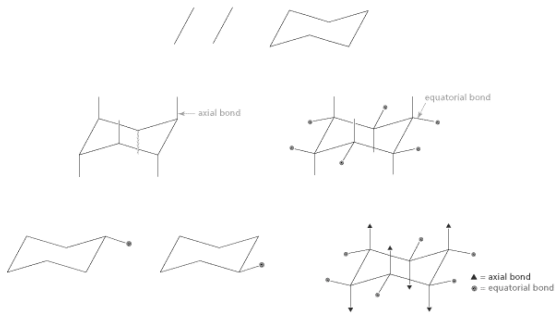
- Less van der Waals strain and less torsional strain in skew boat.

## Generalization

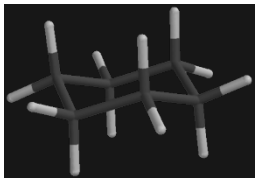
•The chair conformation of cyclohexane is the most stable conformation and derivatives of cyclohexane almost always exist in the chair conformation

*Axial and Equatorial Bonds in Cyclohexane*

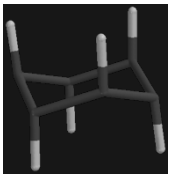
## Drawing Cyclohexane




The 12 bonds to the ring can be divided into two sets of 6.

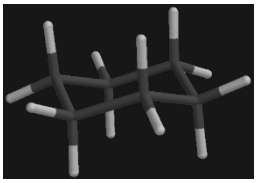


## 6 Bonds are axial

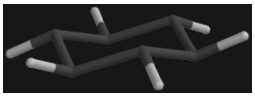


Axial bonds point "north and south"

The 12 bonds to the ring can be divided into two sets of 6.



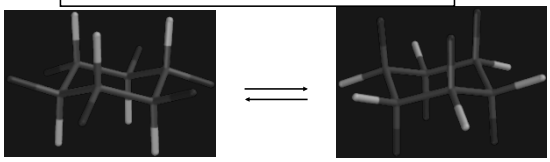
## 6 Bonds are equatorial



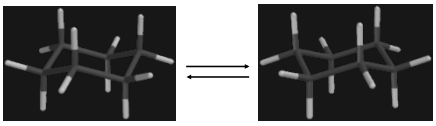
Equatorial bonds lie along the equator

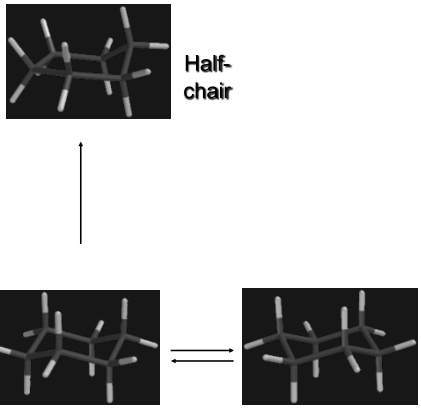
*Conformational Inversion (Ring-Flipping) in Cyclohexane*

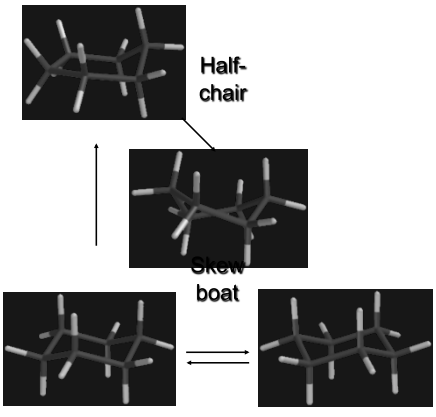
## Conformational Inversion

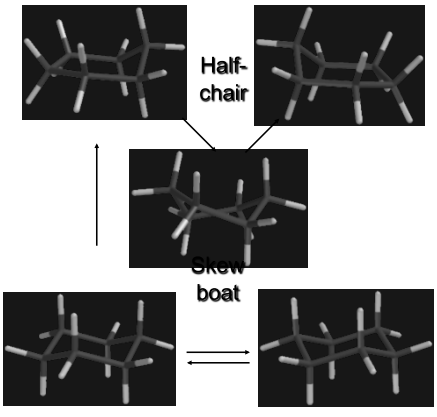


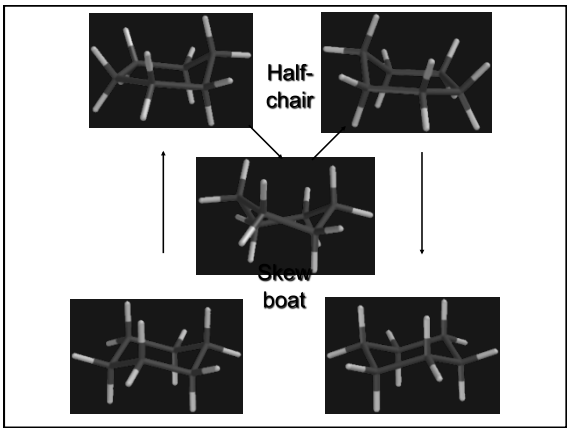
- chair-chair interconversion (ring-flipping)
- rapid process (activation energy = 45 kJ/mol)
- *all axial bonds become equatorial and vice versa*

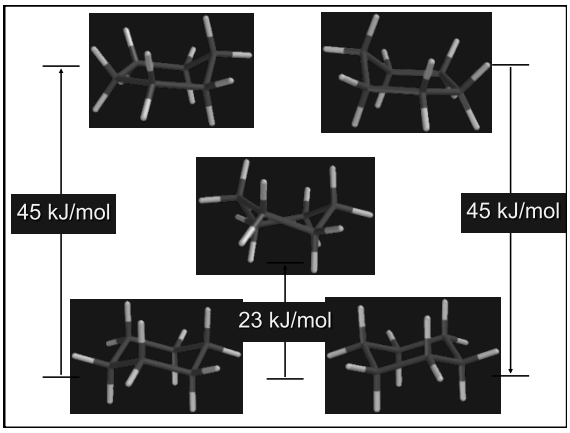




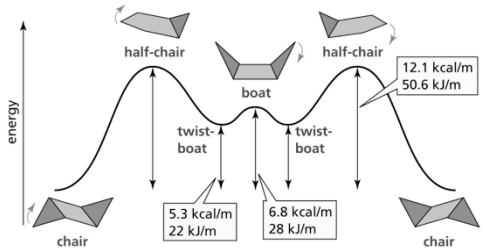





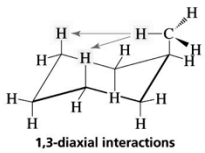

## The Conformations of Cyclohexane and Their Energies

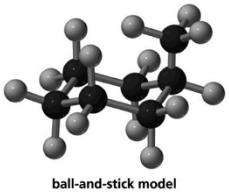



## *Conformational Analysis of Monosubstituted Cyclohexanes*

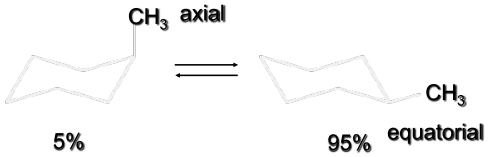
- most stable conformation is chair
- substituent is more stable when equatorial

## Steric Strain of 1,3-Diaxial Interaction in Methylcyclohexane



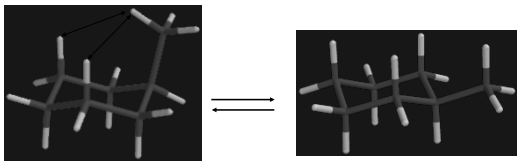




## Methylcyclohexane




- Chair chair interconversion occurs, but at any instant 95% of the molecules have their methyl group equatorial.
- An axial methyl group is more crowded than an equatorial one.

## Methylcyclohexane



5% 95%

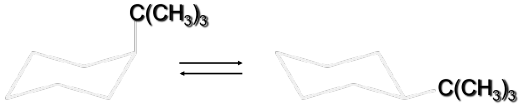
- Hydrogen atoms closer than 2.4 Angstroms will cause steric strain.
- This is called a "1,3-diaxial repulsion" a type of van der Waals strain or Steric strain.

## Fluorocyclohexane


40% 60%

- Crowding is less pronounced with a "small" substituent such as fluorine.
- Size of substituent is related to its branching.

## *tert*-Butylcyclohexane

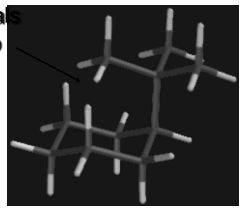



Less than 0.01% Greater than 99.99%

- Crowding is more pronounced with a "bulky" substituent such as *tert*-butyl.
- *tert*-Butyl is highly branched.

## *tert*-Butylcyclohexane

van der Waals strain due to 1,3-diaxial repulsions



- The larger the substituent on a cyclohexane ring, the more the equatorial substituted conformer will be favored

**Table 2.10 Equilibrium Constants for Several Monosubstituted Cyclohexanes at 25 °C**

| Substituent | Axial $\rightleftharpoons$ Equatorial ($K_{eq}$) | Substituent | Axial $\rightleftharpoons$ Equatorial ($K_{eq}$) |
|---|---|---|---|
| H | 1 | CN | 1.4 |
| $CH_3$ | 18 | F | 1.5 |
| $CH_3CH_2$ | 21 | Cl | 2.4 |
| $CH_3CH(CH_3)$ | 35 | Br | 2.2 |
| | | I | 2.2 |
| $CH_3C(CH_3)_2$ | 4800 | HO | 5.4 |

$K_{eq}$ = [equatorial conformer]/[axial conformer]

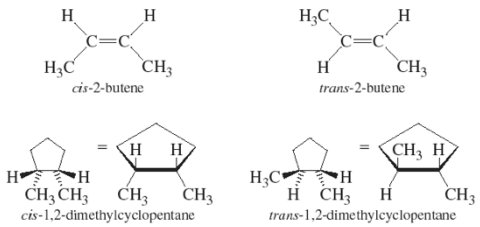
• The larger the substituent on a cyclohexane ring, the more the equatorial substituted conformer will be favored

| SUBSTITUENT | STERIC HINDRANCE FROM 1,3-DIAXIAL INTERACTIONS (KJ/MOL) | AXIAL-EQUATORIAL RATIO (AT EQUILIBRIUM) |
|---|---|---|
| —Cl | 2.0 | 70 : 30 |
| —OH | 4.2 | 83 : 17 |
| $—CH_3$ | 7.6 | 95 : 5 |
| $—CH_2CH_3$ | 8.0 | 96 : 4 |
| $—CH(CH_3)_2$ | 9.2 | 97 : 3 |
| $—C(CH_3)_3$ | 22.8 | 9999 : 1 |

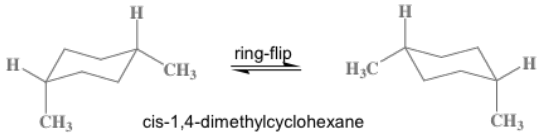
$K_{eq}$ = [equatorial conformer]/[axial conformer]

*Disubstituted Cyclohexanes*
*Cis-trans Isomerism*

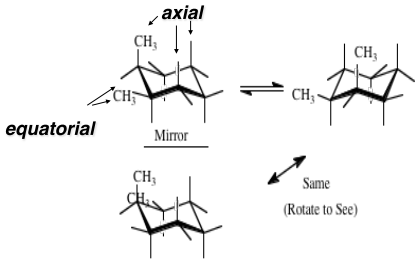
*Cyclic Alkanes Stereochemistry*
*Cis -Trans Isomers*



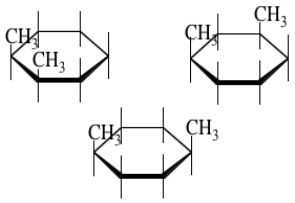

The Chair Conformers of *cis*-1,4-Dimethylcyclohexane




1,2-disubstituted-**cis**-cyclohexane Stereochemistry

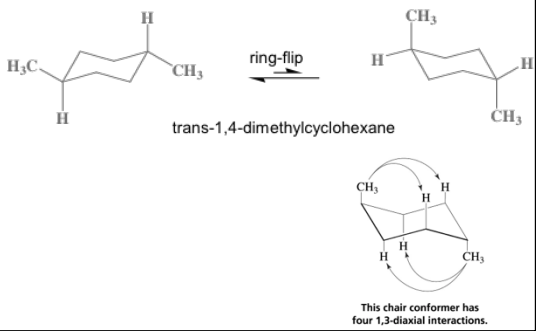



*Cyclohexane Stereochemistry*
*Drawings: Cis isomers & the need for perspective*



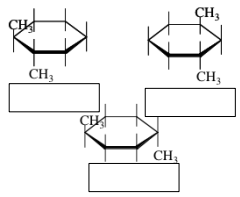
*Are the methyl groups axial or equatorial?*
*What is the actual conformational shape of the cyclohexane ring?*

The Chair Conformers of *trans*-1,4-Dimethylcyclohexane

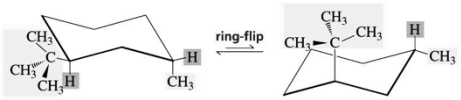


## Cyclohexane Stereochemistry

**Trans** isomers



## 1-*tert*-Butyl-3-Methylcyclohexane




*trans*-1-*tert*-butyl-3-methylcyclohexane

## *Cyclohexane Stereochemistry*

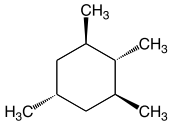
*Cis -Trans Isomers*

| *Position* | *cis* | *trans* |
|---|---|---|
| *1,2* | *e,a or a,e* | *e,e or a,a* |
| *1,3* | *e,e or a,a* | *a,e or e,a* |
| *1,4* | *e,a or a,e* | *e,e or a,a* |

*Complete the Table: a = axial; e = equatorial*

## Question

Consider the molecule below. What is the maximum number of methyl groups that can be in the equatorial position at the same time?



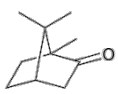
A. 0
B. 1
C. 2
D. 3
E. 4

## Bicyclic Systems

- There are many important structures that result when one ring is fused to another.

.

Bicyclo[2.2.1]heptane (norbornane)



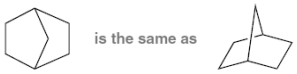
Camphor

Camphene

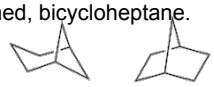
- Camphor, which you smelled the first day of class, and camphene are fragrant natural products isolated from evergreens.

## Naming Compounds – Bicyclic Compounds

- There are many bicyclic compounds with two fused rings.



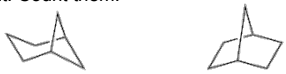

- To name a bicyclic compound, include the prefix "bicyclo" in front of the normal name ending in -ane. For example, the compounds below could both be named, bicycloheptane.



## Naming – Bicyclic Compounds

- We know that if two molecules are not identical, they cannot have the same exact name.

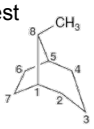
The number of carbons connecting the bridgeheads is different. Count them.

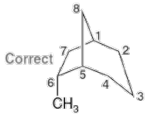


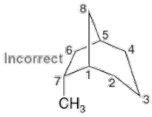
Bicyclo[3.1.1]heptane  Bicyclo[2.2.1]heptane

## Naming– Bicyclic Compounds

1. To number the bicyclo parent chain, start at a bridgehead carbon and number the longest carbon chain connecters first.

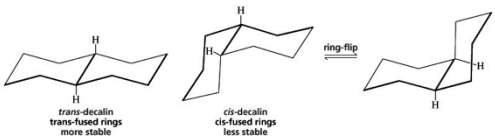




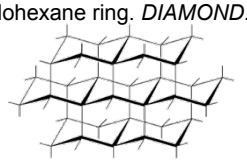




2. Without violating rule 1 above, give the substituents the lowest numbers possible.
- Practice with SKILLBUILDER 4.5.

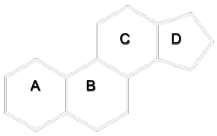
## Conformations of Fused Rings




- Trans-fused cyclohexane ring is more stable than cis-fused cyclohexane ring. *DIAMOND:*

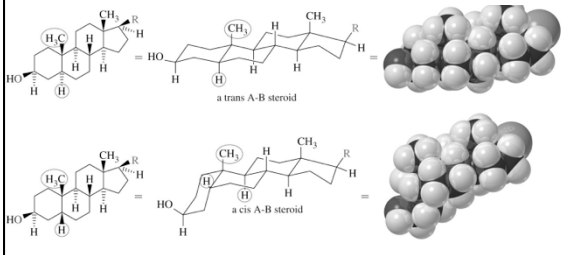


## Cholesterol



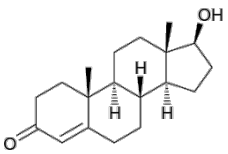

- Fundamental framework of steroids is the tetracyclic unit shown.

## Conformations of Fused Rings

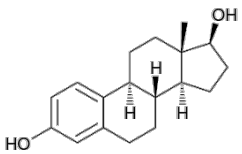



## Hormonal Steroids

- There are many biologically important steroids, two related to primary sex traits are:



Testosterone



Estradiol