

19<sup>th</sup> – 29<sup>th</sup> July 2018  
Bratislava, SLOVAKIA  
Prague, CZECH REPUBLIC

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## THEORETICAL PROBLEMS

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Language:	



## 50<sup>th</sup> IChO 2018

International Chemistry Olympiad  
SLOVAKIA & CZECH REPUBLIC

BACK TO WHERE IT ALL BEGAN



## Table of Contents

Instructions.....	2
Physical constants and equations .....	3
Problem 1. DNA .....	5
Problem 2. Repatriation of remains in the middle ages.....	10
Problem 3. Emerging electro-mobility .....	17
Problem 4. Column chromatography of radioactive copper .....	23
Problem 5. Bohemian garnet.....	28
Problem 6. Let's go mushrooming .....	34
Problem 7. Cidofovir .....	39
Problem 8. Caryophyllene .....	46



## Instructions

- This theoretical exam booklet contains 53 pages.
- You may begin writing as soon as the **Start** command is given.
- You have **5 hours** to complete the exam.
- All results and answers must be clearly written **in pen in their respective designed areas** on the exam papers. Answers written outside the answer boxes will not be graded.
- You were provided with 3 sheets of scratch paper. If you need more, use the backside of the exam sheets. Remember that **nothing outside the designed areas will be graded**.
- The periodic table and visible light spectrum are not part of this booklet; they are provided separately.
- Use only the pen and calculator provided.
- **The official English version** of the exam booklet is available upon request and serves for clarification only.
- If you need to leave the exam room (to use the toilet or have a snack), wave the blue IChO card. The exam supervisor will come to accompany you.
- The supervisor will announce a 30-minute warning before the **Stop** command.
- You must stop your work immediately when the **Stop** command is announced. Failure to stop writing by  $\frac{1}{2}$  minute or longer will lead to nullification of your theoretical exam.
- After the **Stop** command has been given, place your exam booklet back in your exam envelope and wait at your seat. The exam supervisor will come to collect the envelope.



## Physical constants and equations

Avogadro's constant:	$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$
Universal gas constant:	$R = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
Speed of light:	$c = 2.998 \times 10^8 \text{ m s}^{-1}$
Planck's constant:	$h = 6.626 \times 10^{-34} \text{ J s}$
Faraday constant:	$F = 9.6485 \times 10^4 \text{ C mol}^{-1}$
Standard pressure:	$p = 1 \text{ bar} = 10^5 \text{ Pa}$
Normal (atmospheric) pressure:	$p_{\text{atm}} = 1.01325 \times 10^5 \text{ Pa}$
Zero of the Celsius scale:	273.15 K
Mass of electron:	$m_e = 9.109 \times 10^{-31} \text{ kg}$
Unified atomic mass unit:	$u = 1.6605 \times 10^{-27} \text{ kg}$
Ångström:	$1 \text{ Å} = 10^{-10} \text{ m}$
Electronvolt:	$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$
Watt:	$1 \text{ W} = 1 \text{ J s}^{-1}$
Ideal gas equation:	$pV = nRT$
The first law of thermodynamics:	$\Delta U = q + W$
Power input for electrical device:	$P = VI$ where $V$ is voltage and $I$ electric current
Enthalpy:	$H = U + pV$
Gibbs free energy:	$G = H - TS$ $\Delta G^\circ = -RT \ln K = -zFE_{\text{cell}}^\circ$ $\Delta G = \Delta G^\circ + RT \ln Q$
Reaction quotient $Q$ for a reaction $a A + b B \rightleftharpoons c C + d D$ :	$Q = \frac{[C]^c [D]^d}{[A]^a [B]^b}$
Entropy change:	$\Delta S = \frac{q_{\text{rev}}}{T}$ where $q_{\text{rev}}$ is heat for the reversible process
Heat change for temperature-independent $c_m$ :	$\Delta q = n c_m \Delta T$ where $c_m$ is molar heat capacity



Van 't Hoff equation:

$$\frac{d \ln K}{dT} = \frac{\Delta_r H_m}{RT^2} \Rightarrow \ln \left( \frac{K_2}{K_1} \right) = -\frac{\Delta_r H_m}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right)$$

Henderson–Hasselbalch equation:

$$\text{pH} = \text{p}K_a + \log \frac{[\text{A}^-]}{[\text{HA}]}$$

Nernst–Peterson equation:

$$E = E^\circ - \frac{RT}{zF} \ln Q$$

Energy of a photon:

$$E = \frac{hc}{\lambda}$$

Relation between  $E$  in eV and in J:

$$E/\text{eV} = \frac{E/\text{J}}{q_e/C}$$

Lambert–Beer law:

$$A = \log \frac{I_0}{I} = \epsilon l c$$

Wavenumber:

$$\tilde{\nu} = \frac{\nu}{c} = \frac{1}{2\pi c} \sqrt{\frac{k}{\mu}}$$

Reduced mass  $\mu$  for a molecule AX:

$$\mu = \frac{m_A m_X}{m_A + m_X}$$

Energy of harmonic oscillator:

$$E_n = h\nu \left( n + \frac{1}{2} \right)$$

Arrhenius equation:

$$k = A e^{-\frac{E_a}{RT}}$$

Rate laws in integrated form:

Zero order:

$$[\text{A}] = [\text{A}]_0 - kt$$

First order:

$$\ln[\text{A}] = \ln[\text{A}]_0 - kt$$

Second order:

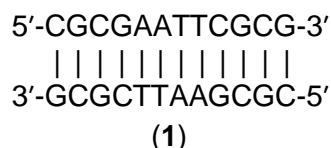
$$\frac{1}{[\text{A}]} = \frac{1}{[\text{A}]_0} + kt$$



Theoretical Problem 1  7% of the total	Question	1.1	1.2	1.3	1.4	1.5	1.6	Total
	Points	5	5	4	12	12	24	62
	Score							

## Problem 1. DNA

Palindromic sequences are an interesting class of DNA. In a palindromic double-stranded DNA (dsDNA) species, the sequence of one strand read in the 5'→3' direction matches the 5'→3' reading on the complementary strand. Hence, a palindromic dsDNA consists of two identical strands that are complementary to each other. An example is the so-called Drew–Dickerson dodecanucleotide (1):



- 1.1 How many different palindromic double-stranded DNA dodecanucleotides (i.e., dsDNA species with twelve base pairs) exist?

- 1.2 How many different palindromic double-stranded DNA undecanucleotides (i.e., dsDNA species with eleven base pairs) exist?

The melting temperature of dsDNA,  $T_m$  is defined as the temperature at which 50% of the original amount of DNA double strands are dissociated into separate strands.

- 1.3 Consider the Drew–Dickerson dodecanucleotide (1). Assume that a G–C nucleobase pair contributes to the DNA duplex stability more than an A–T pair does. What is the probability that its  $T_m$  increases when a single randomly selected base pair is replaced by a G–C pair?



Probability

Let us analyse the thermodynamics of formation of double-helical DNA from single strands, and its dependence on the length of the DNA and on the temperature. The equilibrium constant of association of single strands to form dsDNA differs for palindromic and non-palindromic dsDNA. A solution of dsDNA with the initial concentration of  $c_{\text{init}} = 1.00 \times 10^{-6} \text{ mol dm}^{-3}$  was heated to  $T_m$  and equilibrium was reached.

- 1.4 Calculate the equilibrium constant of **association** of single strands at  $T_m$  for both non-palindromic and palindromic DNA.

Non-palindromic dsDNA

Show your calculation:

$K =$

Palindromic dsDNA

Show your calculation:



$K =$

The mean contributions to the Gibbs energy of association of two single strands to form dsDNA were estimated over a certain range of experimental conditions, and they amount to  $-6.07 \text{ kJ mol}^{-1}$  per one G–C pair, and  $-1.30 \text{ kJ mol}^{-1}$  per one A–T pair present in a dsDNA.

- 1.5 How many base pairs are there in the **shortest** dsDNA oligonucleotide that has  $T_m$  above 330 K? At this  $T_m$ , consider the following values of the equilibrium constant of association of single strands to form a dsDNA:  $K_{np} = 1.00 \times 10^6$  for a non-palindromic dsDNA,  $K_p = 1.00 \times 10^5$  for a palindromic dsDNA. Is the shortest oligonucleotide palindromic or non-palindromic?

Calculation of the number of base pairs:

The required number of base pairs in non-palindromic dsDNA:

The required number of base pairs in palindromic dsDNA:

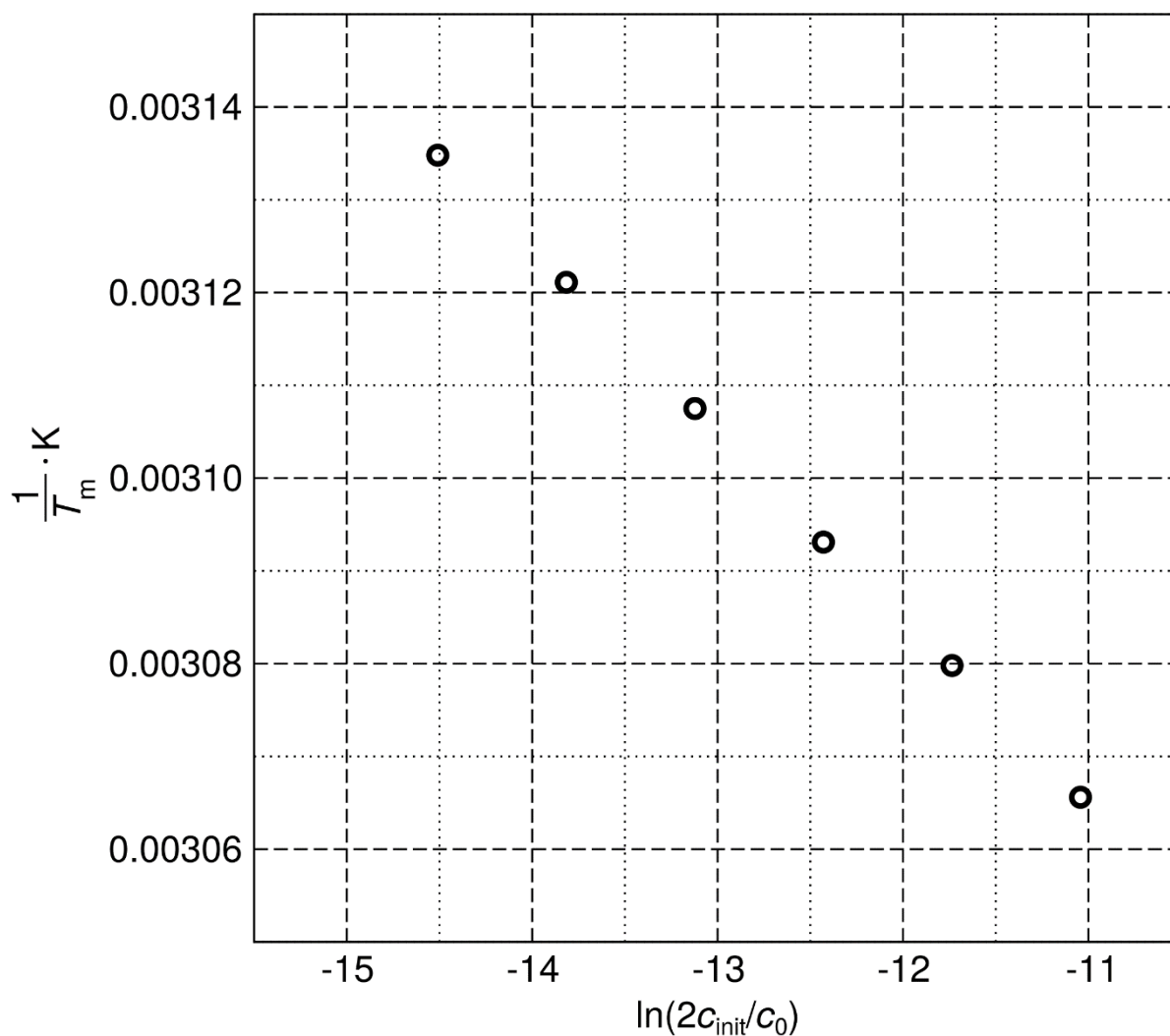
The shortest oligonucleotide is

- palindromic (P)  
 non-palindromic (NP).





Finally, let us leave the simplified idea of base pairs contributing individually to the **association** of DNA strands. The Gibbs energy of this process may be considered explicitly dependent on temperature. The dependence of the inverse  $T_m$  of the Drew–Dickerson dodecanucleotide (1) on the logarithm of the initial duplex concentration  $c_{\text{init}}$  is shown below. (Note: a standard concentration  $c_0 = 1 \text{ mol dm}^{-3}$  is introduced.)



$c_{\text{init}} / 10^{-6} \text{ mol dm}^{-3}$	0.25	0.50	1.00	2.0	4.0	8.0
$T_m / K$	319.0	320.4	321.8	323.3	324.7	326.2



- 1.6 Calculate the standard enthalpy  $\Delta H^\circ$  and the standard entropy  $\Delta S^\circ$  of the association of DNA single strands to form the palindromic double-stranded Drew–Dickerson dodecanucleotide (1). Assume that  $\Delta H^\circ$  and  $\Delta S^\circ$  do not vary with temperature.

Show your calculation:



Theoretical Problem 2  8% of the total	Question	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	Total
	Points	1	4	4	2	6	10	17	14	58
	Score									

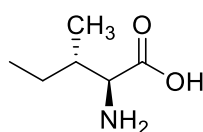
## Problem 2. Repatriation of remains in the middle ages

At ambient temperatures, racemisation is a slow reaction. As such, it can be used for dating biological objects and, moreover, for studying their thermal history. Let us take L-isoleucine (L-Ile) ((2*S*,3*S*)-2-amino-3-methylpentanoic acid) as an example. It isomerises on the  $\alpha$ -carbon and forms (2*R*,3*S*)-2-amino-3-methylpentanoic acid, also known as D-*allo*-isoleucine. As the configuration changes on only one of the two stereogenic centres, this process is called epimerisation rather than racemisation.

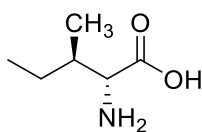
2.1 Choose all true statements.

- D-*allo*-isoleucine and L-isoleucine have the same values of specific optical rotation but they have different melting points.
- D-*allo*-isoleucine has an identical absolute value of specific optical rotation as L-isoleucine but the sign is opposite. The melting point is the same for both isomers.
- D-*allo*-isoleucine and L-isoleucine have different values of specific optical rotation but they have the same melting points.
- D-*allo*-isoleucine and L-isoleucine have different values of specific optical rotation and different melting points.
- D-*allo*-isoleucine is not optically active.

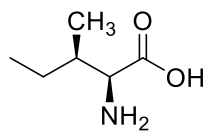
2.2 Assign the absolute configurations for each stereoisomer of isoleucine.



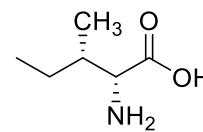
A



B



C



D

- 2*S*,3*R* (L-*allo*-isoleucine)
- 2*R*,3*S* (D-*allo*-isoleucine)
- 2*S*,3*S* (L-isoleucine)
- 2*R*,3*R* (D-isoleucine)



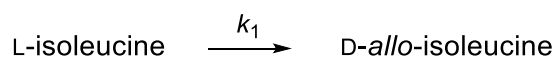
- 2.3 The equilibrium constant  $K_{ep}$  for L-isoleucine epimerisation has the value of 1.38 (at 374 K). Setting the molar Gibbs free energy of L-isoleucine  $G_m^\circ = 0 \text{ kJ mol}^{-1}$ , determine the Gibbs free energies for all structures **A–D** from question 2.2 at 374 K.

<b>A</b>	$\text{kJ mol}^{-1}$
<b>B</b>	$\text{kJ mol}^{-1}$
<b>C</b>	$\text{kJ mol}^{-1}$
<b>D</b>	$\text{kJ mol}^{-1}$

- 2.4 If we take into account stereoisomerism at all stereocentres, what is the maximum possible number of the stereoisomers of the tripeptide Ile-Ile-Ile?

The number of stereoisomers is

At the start of the epimerisation, we can neglect the reverse reaction. The epimerisation then follows the first-order kinetics:



The value of the rate constant at 374 K is  $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$  and at 421 K it is  $k_1(421 \text{ K}) = 1.18 \times 10^{-2} \text{ h}^{-1}$ .

In the following calculation, shorten the concentration of L-isoleucine to [L] and of D-*allo*-isoleucine to [D].

We can define a quantity *de* (diastereomeric excess):

$$de = \frac{[L] - [D]}{[L] + [D]} \times 100(\%).$$



- 2.5 Let us boil L-isoleucine for 1 943 hours at 374 K. What is the value of  $d_e$  (with three significant figures) for L-isoleucine a) before boiling and b) after boiling?

a) Before boiling

Show your calculation:

$d_e =$             % (with 3 significant figures)

b) After boiling

Show your calculation:

$d_e =$             % (with 3 significant figures)

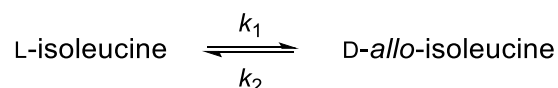
- 2.6 How long does it take to convert 10% of L-isoleucine to D-*allo*-isoleucine at 298 K?

Show your calculation:



t =                      years

In fact, the reverse reaction cannot be neglected. The correct kinetic scheme is expressed as



Let us define the deviation of concentration from its equilibrium value  $[L]_{\text{eq}}$

$$x = [L] - [L]_{\text{eq}}$$

It is possible to derive that  $x$  evolves with time according to the following equation:

$$x = x(0) \times e^{-(k_1 + k_2)t},$$

where  $x(0)$  is the deviation from equilibrium at  $t = 0$  h.

- 2.7 Let us boil  $1.00 \text{ mol dm}^{-3}$  L-isoleucine solution for 1 943 hours at 374 K. The rate constant for the forward reaction is  $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$ ,  $K_{\text{ep}}$  for L-isoleucine epimerisation has the value of 1.38 (at 374 K). In the following calculation, shorten the concentration of L-isoleucine to  $[L]$  and of D-*allo*-isoleucine to  $[D]$ . Evaluate (with three significant figures) a)  $[L]_{\text{eq}}$ , b) diastereomeric excess ( $de$ ) after boiling.



a) Show your calculation:

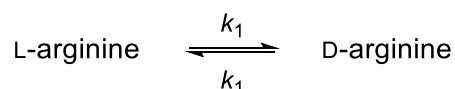
$[L]_{\text{eq}} =$              $\text{mol dm}^{-3}$

b) Show your calculation:



$de =$             % (with 3 significant figures)

Amino acids with a single chiral centre undergo racemisation, e.g. L-arginine racemises:



The time evolution of concentrations is governed by

$$\ln \frac{1 + \frac{[D]}{[L]}}{1 - \frac{[D]}{[L]}} = 2k_1 t + C$$

Here [D] and [L] are concentrations of D- and L-arginine at time  $t$ ,  $k_1$  is the rate constant, and the term  $C$  is set according to the initial concentrations.

Holy Roman Emperor Lothar III passed away during his journey to Sicily in 1137. To facilitate the repatriation of the remains, his body was, immediately after his death, boiled in water (at 373 K) for a certain time. Let us try to estimate the boiling time with the help of chemical kinetics. We know that the rate constant  $k_1$  of arginine racemisation within the protein at 373 K and pH = 7 has the value of  $5.10 \times 10^{-3} \text{ h}^{-1}$ .

In order to analyse the isomeric composition of arginine in Lothar's bones, we need to start with transferring arginine into solution. Lothar's bones were hydrolysed in a highly acidic environment for





4 hours at 383 K. The ratio of the optical isomers was  $\frac{[D]}{[L]} = 0.090$ . Lothar's wife Richenza was not boiled after her death. Her bones were hydrolysed using the same procedure and in this case the ratio was  $\frac{[D]}{[L]} = 0.059$ . (Note that the racemisation also takes place during the hydrolysis, with the rate constant  $k_1'$ , different from  $k_1$ ).

2.8 How long was the Holy Roman Emperor Lothar III boiled in water in 1137?

*Note:* The racemisation of arginine is an extremely slow process at temperatures typically encountered in graves. As both bodies are only some 880 years old, we can neglect the natural racemisation during this time.

Show your calculation:

$t_{\text{boiling}} =$  h



<b>Theoretical Problem 3</b> 8% of the total	Question	3.1	3.2	3.3	3.4	3.5	3.6
	Points	2	6	7	3	7	8
	Score						
	Question	3.7	3.8	3.9	3.10	3.11	<b>Total</b>
	Points	6	10	5	2	6	<b>62</b>
	Score						

### Problem 3. Emerging electro-mobility

Contemporary means of transportation rely on burning fossil fuels, although the efficiency of real combustion engines is inherently limited and typically ranges between 20 and 40%.

3.1 Mark the factors that can make the efficiency of a heat engine higher:

- Increasing the friction in the mechanical parts of the engine
- Increasing the burning temperature of the fuel in the engine
- Narrowing the working temperature interval of the engine
- Increasing the working pressure of the gas

Fuel cells represent a way to improve the engine efficiency for future vehicles. The engine efficiency can be improved by using hydrogen-based fuel cells.

3.2 The standard enthalpy of formation of liquid water is  $\Delta_f H^\circ(\text{H}_2\text{O}, \text{l}) = -285.84 \text{ kJ mol}^{-1}$ , and the standard combustion enthalpy of isooctane is  $\Delta_c H^\circ(\text{C}_8\text{H}_{18}, \text{l}) = -5065.08 \text{ kJ mol}^{-1}$  (both at 323.15 K). Calculate the values of specific (per unit of mass) combustion enthalpy at 323.15 K of pure liquid isooctane and pure gaseous hydrogen.

$$\Delta_c H_s^\circ(\text{C}_8\text{H}_{18}) =$$

$$\Delta_c H_s^\circ(\text{H}_2) =$$



- 3.3 Calculate the standard electromotive force (EMF) of a fuel cell using gaseous oxygen and hydrogen, both ideal gases at 100 kPa and 323.15 K, to produce liquid water. Use the following entropy data for 323.15 K:  $S^\circ(\text{H}_2\text{O},\text{l}) = 70 \text{ J K}^{-1} \text{ mol}^{-1}$ ,  $S^\circ(\text{H}_2,\text{g}) = 131 \text{ J K}^{-1} \text{ mol}^{-1}$ ,  $S^\circ(\text{O}_2,\text{g}) = 205 \text{ J K}^{-1} \text{ mol}^{-1}$ .

Show your calculation:

EMF =            V

- 3.4 Determine the ideal thermodynamic efficiency ( $\eta$ ) of a fuel cell producing liquid water at 353.15 K. At this temperature, the enthalpy of formation of water is  $\Delta_f H^\circ(\text{H}_2\text{O},\text{l}) = -281.64 \text{ kJ mol}^{-1}$  and the corresponding reaction Gibbs energy change is  $\Delta_r G^\circ = -225.85 \text{ kJ mol}^{-1}$ .

$\eta =$             %

- 3.5 A polymer membrane electrolyser facility operates at the voltage of 2.00 V and is powered by a 10.0 MW wind turbine plant which was running at full power from 10 pm to 6 am. The electrolysis yielded 1090 kg of pure hydrogen. Calculate the electrolysis yield defined as the mass of produced hydrogen divided by its theoretical produced mass.

Show your calculation:



$\eta_{\text{electrolysis}} =$                       %

- 3.6 Calculate the mass of hydrogen required to drive the distance between Prague and Bratislava (330 km) at the average speed of  $100 \text{ km h}^{-1}$  with a car fitted with a 310 kW electric engine running on average at 15% of its maximum power. Assume that the efficiency of the hydrogen cell producing electrical energy is 75%, the efficiency of the electric engine is 95%, and the Gibbs energy change for combustion of hydrogen fuel is  $\Delta_r G = -226 \text{ kJ mol}^{-1}$ .

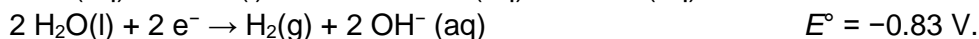
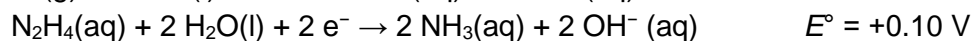
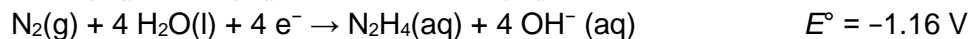
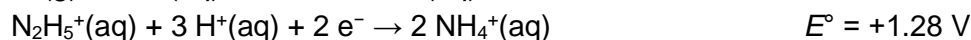
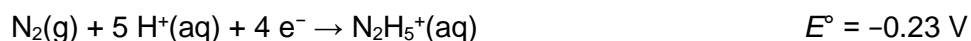
Show your calculation:

$m =$                       kg

The low efficiency of hydrogen production and the safety issues connected with its storage impede spreading the hydrogen-based transportation technology. Hydrazine ( $\text{N}_2\text{H}_4$ ) fuel cells might be a suitable alternative.

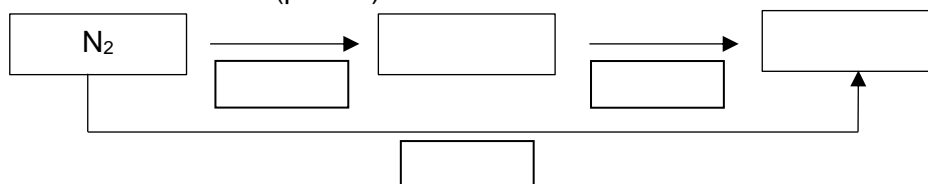


The following standard reduction potentials for aqueous hydrazine systems are available:

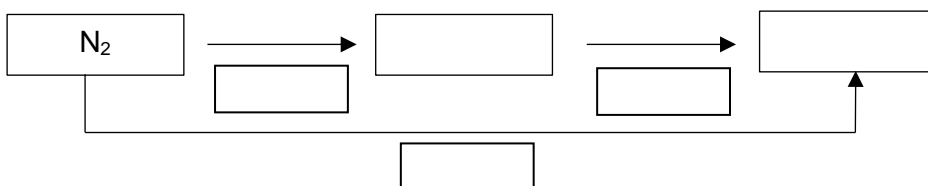


3.7 Fill in the following Latimer diagrams with the forms of hydrazine and ammonia prevailing at the given conditions and write the redox potential value for each arrow representing the electrochemical half-reaction. Record all the necessary calculations.

a) Acidic environment (pH = 0)



b) Basic environment (pH = 14)



Show your calculations:

Due to the toxicity, odour and its environmental impact, it is extremely unfavourable to produce ammonia in fuel cells.



- 3.8 Write down the net reaction for the decomposition of hydrazine under basic conditions to (i) ammonia and nitrogen and (ii) nitrogen and hydrogen and calculate the corresponding equilibrium constants at  $T = 298.15$  K.

Equations for hydrazine decomposition:

Show your calculations:

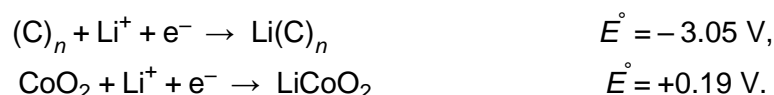
Hydrazine decomposition to  $\text{NH}_3$  and  $\text{N}_2$  in a basic environment:

$K =$

Hydrazine decomposition to  $\text{H}_2$  and  $\text{N}_2$  in a basic environment:

$K =$

Rechargeable lithium-based batteries are an alternative to fuel cells. Lithium-ion batteries commonly use graphite for one of the electrodes, in which lithium clusters intercalate in between the graphite sheets. The other electrode is made of lithium cobalt oxide, which can reversibly absorb lithium ions moving from one electrode to the other during the charge and discharge processes. The half-reactions relevant for the system can be formally written as:



- 3.9 Using the formalism given above, write down the overall chemical reaction occurring in the battery during the **discharge** process. Give the oxidation states of the cobalt atom.



3.10 Tick the boxes which are correct for the **discharge** of the lithium-based battery described in 3.9:

Li(C) <sub>n</sub> electrode is the	<input type="checkbox"/>	cathode	<input type="checkbox"/>	because lithium ions are reduced here.
	<input type="checkbox"/>	anode	<input type="checkbox"/>	because lithium atoms are oxidised here.
LiCoO <sub>2</sub> electrode is the	<input type="checkbox"/>	cathode	<input type="checkbox"/>	because cobalt ions are reduced here.
	<input type="checkbox"/>	anode	<input type="checkbox"/>	because cobalt ions are oxidised here.

3.11 Assume that a C<sub>6</sub> unit, a CoO<sub>2</sub> unit and Li atom form the active battery mass required to transfer one electron between the electrodes. Using the corresponding standard EMF, calculate the theoretical specific reversible charge capacity (in mAh g<sup>-1</sup>) and the energy density (in kWh kg<sup>-1</sup>) of such a model lithium ion battery related to the whole active battery mass.

Show your calculation:

Charge capacity ( $c_{q,s}$ ) = \_\_\_\_\_ mAh g<sup>-1</sup>

Show your calculation:

Energy density ( $\rho_{el}$ ) = \_\_\_\_\_ kWh kg<sup>-1</sup>

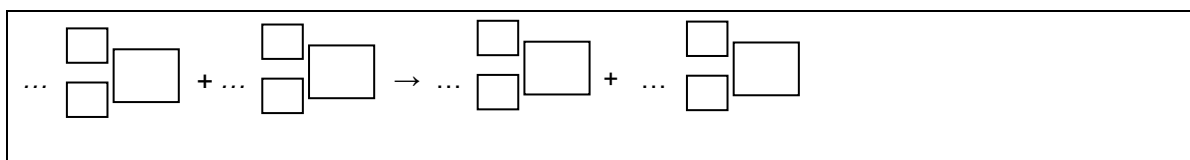


Theoretical Problem 4	Question	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	Total
	6% of the total	Points	2	5	1	2	7	2	3	2
	Score									

## Problem 4. Column chromatography of radioactive copper

$^{64}\text{Cu}$  for positron emission tomography is prepared by the bombardment of a zinc target with deuterium nuclei (further referred to as the activated target).

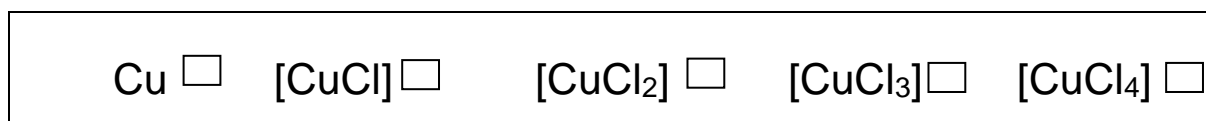
- 4.1 Write down the balanced equation for the  $^{64}\text{Zn}$  nucleus bombardment with deuterium nuclei, giving  $^{64}\text{Cu}$ . Specify the corresponding atomic and mass numbers of all species. Disregard the charges of the species.



The activated target is dissolved in concentrated hydrochloric acid ( $\text{HCl (aq)}$ ) to give a mixture containing  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  ions and their respective chlorido complexes.

- 4.2 Calculate the mole fraction of negatively charged copper species with respect to the amount of copper prepared by zinc target activation. Assume  $[\text{Cl}^-] = 4 \text{ mol dm}^{-3}$ . For the overall complexation constants,  $\beta$ , see Table 1.

Before you start the calculation, write down the charges in the upper right boxes:



	$i$ in $[\text{CuCl}_i]$			
	1	2	3	4
$\beta_i$	2.36	1.49	0.690	0.055

Table 1. Overall complexation constants  $\beta$  of Cu species (charges have been omitted in the formula).

$$\beta_i = \frac{[\text{CuCl}_i]}{[\text{Cu}] \cdot [\text{Cl}]^i}$$





Show your calculation:

Mole fraction =

(answer with 2 digits after decimal point)

The mixture containing  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  ions and their respective chlorido complexes was separated with an anion exchange resin. Dry resin in  $\text{OH}^-$  form was dispersed in water and the suspension was transferred into a column. To occupy all sites with  $\text{Cl}^-$  ions (i.e. to obtain resin in a  $\text{Cl}^-$  form), the resin was washed with hydrochloric acid and then with deionised water to wash out all the unbound  $\text{Cl}^-$  ions.

4.3 Everything was initially at laboratory temperature before washing with hydrochloric acid. Does the column temperature change during the washing with hydrochloric acid?

- No.
- Yes, the temperature decreases.
- Yes, the temperature increases.

The mixture containing  $\text{Cu}^{2+}$  and  $\text{Zn}^{2+}$  ions and their respective chlorido complexes was transferred onto the resin-filled column. Hydrochloric acid solution was used as an eluent.

Using the simple experimental formula below, you can calculate quantities that determine average elution properties of both copper species and zinc species on the column.

The retention volume  $V_R$  (the mobile phase volume at which 50% of the compound has been eluted from the column) can be calculated as follows:

$$V_R = D_g \times m_{\text{resin,dry,OH form}} + V_0$$



- 4.4 Using the average mass distribution coefficients  $D_g$  ( $D_g(\text{Cu species}) = 17.4 \text{ cm}^3 \text{ g}^{-1}$ ,  $D_g(\text{Zn species}) = 78.5 \text{ cm}^3 \text{ g}^{-1}$ ), calculate the retention volume  $V_R$  in  $\text{cm}^3$  of the copper species, and of the zinc species. The mass of dry resin in  $\text{OH}^-$  form  $m_{\text{resin,dry,OH form}} = 3.72 \text{ g}$  and the void volume of a column  $V_0 = 4.93 \text{ cm}^3$ .

Show your calculation:

$V_R(\text{Cu species}) =$   $\text{cm}^3$  (answer with 1 digit after the decimal point)

$V_R(\text{Zn species}) =$   $\text{cm}^3$  (answer with 0 digit after the decimal point)

If you cannot find the answer, use  $V_R(\text{Cu species}) = 49.9 \text{ cm}^3$  and  $V_R(\text{Zn species}) = 324 \text{ cm}^3$  for further calculations.

Using this simple experimental formula, separation of two sets of species, **A** and **B**, can be considered complete if

$$V_{0.001}(\mathbf{A}) - V_{0.999}(\mathbf{B}) > 10V_c$$

where  $V_{0.001}$  is the mobile phase volume at which 0.1% of **A** has been eluted from the column, and  $V_{0.999}$  is the mobile phase volume at which 99.9% of **B** has been eluted from the column.

$$V_{0.001}(\mathbf{A}) = V_R(\mathbf{A}) \times \left(1 - 6.91 \sqrt{d_p/L_c}\right)$$

$$V_{0.001}(\mathbf{B}) = V_R(\mathbf{B}) \times \left(1 - 6.91 \sqrt{d_p/L_c}\right)$$

$$V_{0.999}(\mathbf{B}) = 2V_R(\mathbf{B}) - V_{0.001}(\mathbf{B})$$



- 4.5 Based on a calculation, decide whether copper species were separated completely from zinc species. The volume of the column filled with the swollen resin  $V_c = 10.21 \text{ cm}^3$ , the resin particle diameter  $d_p = 0.125 \text{ mm}$ , and the height of the wet resin in a swollen state in the column  $L_c = 13.0 \text{ cm}$ .

$$V_{0.001}(A) = \quad \text{cm}^3$$

$$V_{0.999}(B) = \quad \text{cm}^3$$

It is possible to separate copper species from zinc species.

True       False

- 4.6 Calculate the theoretical value of the total ion exchange mass capacity of the dry resin used in this problem,  $Q_{m,\text{theor}}$ , in  $\text{mmol g}^{-1}$ . Assume that tetralkylammonium groups were the only ones responsible for ion exchange of the resin. No other nitrogen containing groups were present. The mass fraction of nitrogen in the dry resin was 4.83%.

$$Q_{m,\text{theor}} = \quad \text{mmol g}^{-1} \text{ (answer with 2 digits after decimal point)}$$

If you cannot find the answer, use  $Q_{m,\text{theor}} = 4.83 \text{ mmol g}^{-1}$  for further calculations.



In reality, not all tetraalkylammonium groups are involved in the ion exchange. To determine the total ion exchange volume capacity,  $Q_v$ , the column filled with 3.72 g dry resin converted to the  $\text{Cl}^-$  form was washed with the excess of sodium sulfate solution. The effluent was collected in a  $500 \text{ cm}^3$  volumetric flask, which was then filled with water to the mark. An aliquot of  $100 \text{ cm}^3$  was potentiometrically titrated with  $0.1027 \text{ mol dm}^{-3}$  silver nitrate. The silver nitrate solution volume at the equivalence point was  $22.20 \text{ cm}^3$ . The volume of the column filled with the swollen resin,  $V_c$ , was  $10.21 \text{ cm}^3$ .

- 4.7 Calculate the  $Q_v$  of the swollen resin in mmol of active tetraalkylammonium groups per  $\text{cm}^3$  of the swollen resin.

$Q_v =$  \_\_\_\_\_ mmol  $\text{cm}^{-3}$  (answer with 2 digits after decimal point)

If you cannot find the answer, use  $Q_v = 1.00 \text{ mmol cm}^{-3}$  for further calculations.

- 4.8 Calculate the mole fraction ( $x$ ) of the tetraalkylammonium groups actively involved in the ion exchange.

$x =$  \_\_\_\_\_ (answer with 3 digits after decimal point)



<b>Theoretical Problem 5</b>	Question	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
	Points	3	3	1	5	3	2	4	1	2
	Score									
8% of the total	Question	5.10	5.11	5.12	5.13	5.14	5.15	5.16	5.17	<b>Total</b>
	Points	5	7	3	2	6	1	1	1	<b>50</b>
	Score									

## Problem 5. Bohemian garnet

Bohemian garnet (pyrope) is a famous Czech blood-coloured semi-precious stone. The chemical composition of natural garnets is expressed by the general stoichiometric formula of  $A_3B_2(\text{SiO}_4)_3$ , where  $A^{\text{II}}$  is a divalent cation and  $B^{\text{III}}$  is a trivalent cation. Garnets have a cubic unit cell that contains 8 formula units. The structure comprises 3 types of polyhedra: the  $A^{\text{II}}$  cation occupies a dodecahedral position (it is surrounded by eight O atoms), the  $B^{\text{III}}$  cation occupies an octahedral position (it is surrounded by six O atoms) and  $\text{Si}^{\text{IV}}$  is surrounded by four O atoms arranged into a tetrahedron.

The most common garnet mineral is almandine with the formula of  $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$ . Its unit cell parameter is  $a = 11.50 \text{ \AA}$ .

5.1 Calculate the theoretical density of almandine.

$\rho =$                        $\text{g cm}^{-3}$

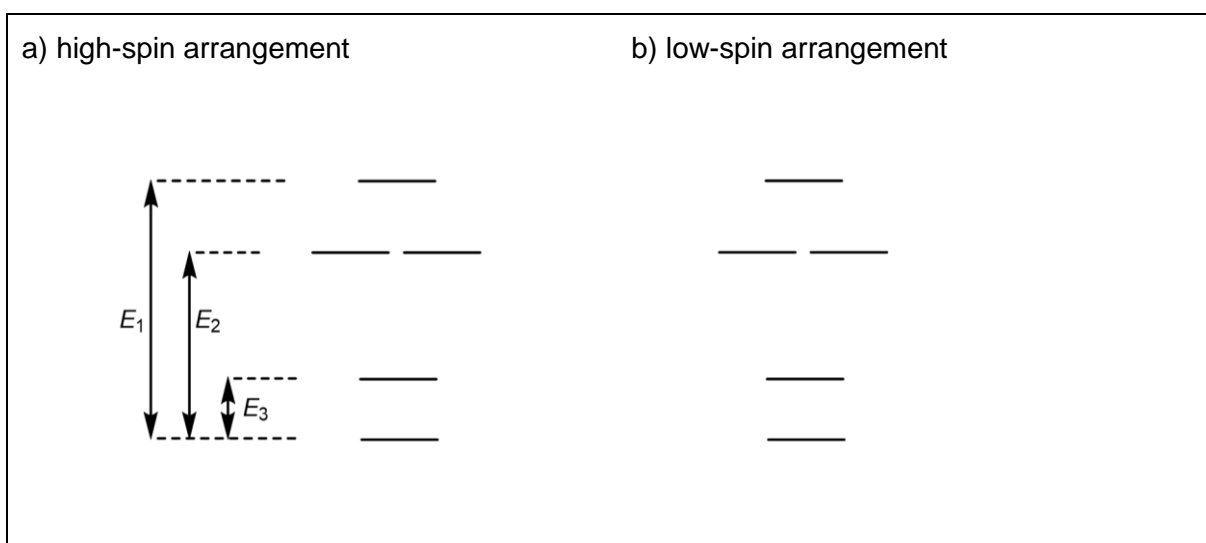
The Bohemian garnet has the composition of  $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$ . The pure compound is colourless and the colour of natural garnets comes from chromophores – transition metal cations that substitute the host material cations. The red colour of the Bohemian garnet comes from trace amounts of  $\text{Cr}^{\text{III}}$  ions in the octahedral sites and  $\text{Fe}^{\text{II}}$  ions in the dodecahedral sites.

5.2 Draw the splitting diagram for the  $[\text{Cr}^{\text{III}}\text{O}_6]^{\text{oct}}$  d-orbitals and fill it with electrons.



- 5.3 Identify the 1<sup>st</sup> transition row element(s) whose trivalent cation(s)  $M^{III}$  placed in an **octahedral** position is/are diamagnetic in the low-spin arrangement and paramagnetic in the high-spin arrangement.

- 5.4 The figure below shows d-orbital splitting in a dodecahedral crystal field. Fill in the electrons for the  $[Fe^{II}O_8]^{dod}$  chromophore for both existing arrangements.



- 5.5 Derive inequalities (e.g.  $P < E_1 + E_2 + E_3$ ) for the pairing energy ( $P$ ) magnitude in relation to energies  $E_1$ ,  $E_2$  and  $E_3$  for both arrangements.

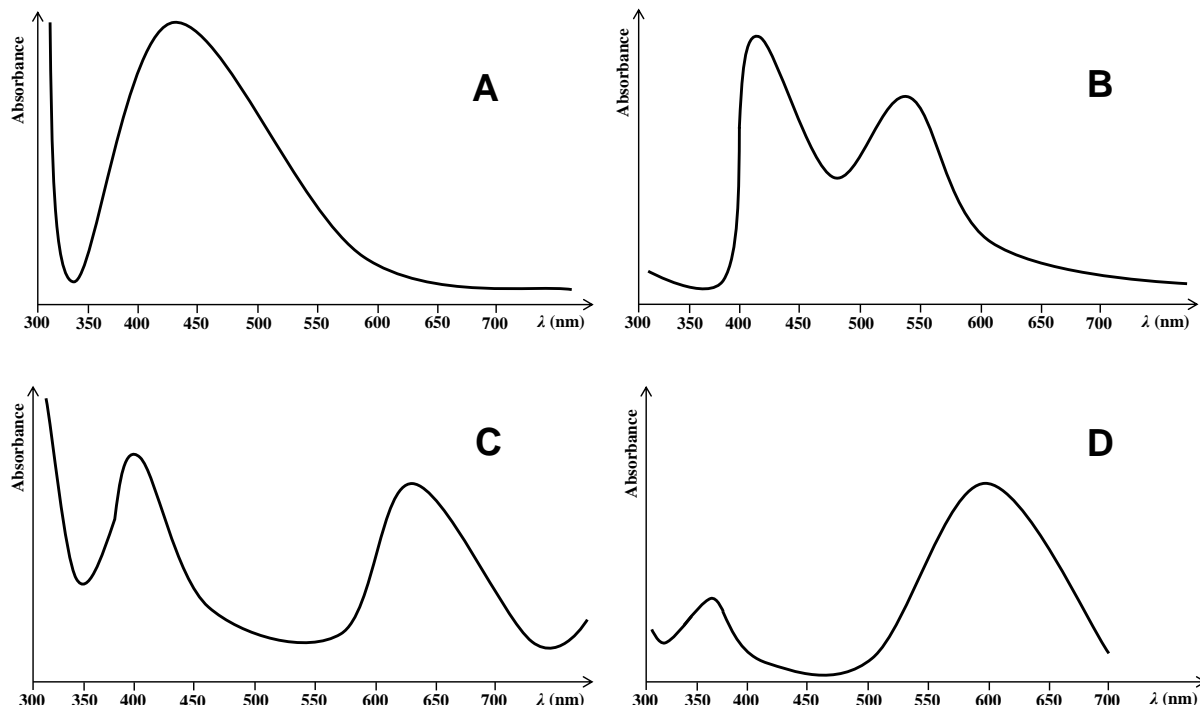
a) high-spin arrangement:  $P$

b) low-spin arrangement:  $P$

- 5.6 Assuming that  $P > E_3$ , identify the 1<sup>st</sup> transition row element(s) whose divalent cation  $M^{II}$  placed in dodecahedral position is diamagnetic in the low-spin arrangement and paramagnetic in the high-spin arrangement.



The figures below show simplified absorption spectra of four coloured minerals – blood-coloured Bohemian garnet, green uvarovite, blue sapphire and yellow-orange citrine.



5.7 Match the spectra with the minerals.

Bohemian garnet:	Sapphire:
Uvarovite:	Citrine:

5.8 If illuminated with monochromatic blue-green light, how will the Bohemian garnet appear?

<input type="checkbox"/> Red	<input type="checkbox"/> Blue	<input type="checkbox"/> Yellow-orange	<input type="checkbox"/> Black
<input type="checkbox"/> Yellow	<input type="checkbox"/> Blue-green	<input type="checkbox"/> Violet	<input type="checkbox"/> White

Andradite is another garnet mineral; its chemical composition is  $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$ . A double cation substitution –  $\text{Ti}^{\text{IV}}$  for  $\text{Fe}^{\text{III}}$  in the octahedral position and  $\text{Fe}^{\text{III}}$  for  $\text{Si}^{\text{IV}}$  in the tetrahedral position – gives rise to black schorlomite. Its chemical composition can be expressed as  $\text{Ca}_3[\text{Fe}, \text{Ti}]_2^{\text{oct}}([\text{Si}, \text{Fe}]^{\text{tet}}\text{O}_4)_3$ .

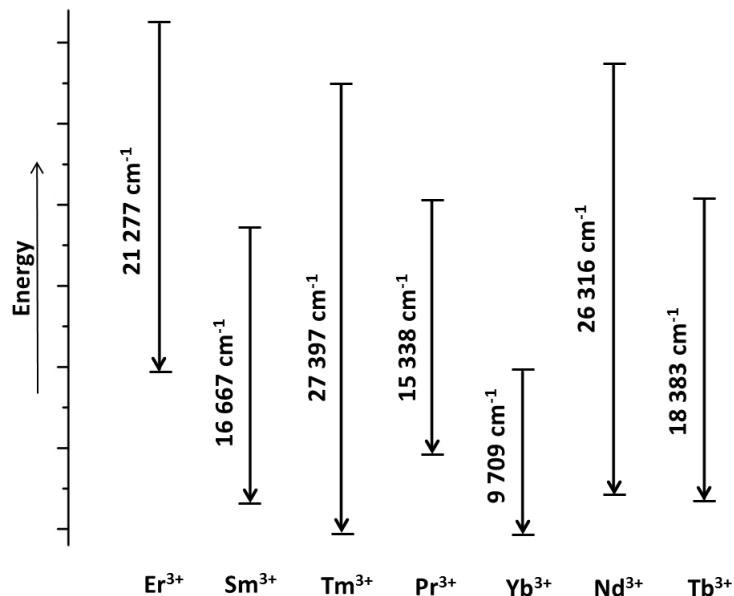








Doping the YAG structure with rare-earth ions enables the production of lasers with emission wavelengths ranging from the UV to the mid-IR region. In the scheme below, simplified f–f energy transitions of selected rare-earth ions are shown.



5.15 Which cation has a transition which corresponds to blue light emission.

<input type="checkbox"/> Er <sup>3+</sup>	<input type="checkbox"/> Sm <sup>3+</sup>	<input type="checkbox"/> Tm <sup>3+</sup>	<input type="checkbox"/> Pr <sup>3+</sup>
<input type="checkbox"/> Yb <sup>3+</sup>	<input type="checkbox"/> Nd <sup>3+</sup>	<input type="checkbox"/> Tb <sup>3+</sup>	

5.16 Calculate the emission wavelength of this light.

$\lambda =$ nm
----------------

5.17 According to a legend, Noah used a stick with a garnet stone for illumination during his voyage. Assuming only the photoluminescence effect, determine the colour of the laser light emitted from his stick if the stone were the blood-coloured Bohemian garnet.

<input type="checkbox"/> Red	<input type="checkbox"/> Blue	<input type="checkbox"/> Yellow-orange	<input type="checkbox"/> Black
<input type="checkbox"/> Yellow	<input type="checkbox"/> Blue-green	<input type="checkbox"/> Violet	<input type="checkbox"/> White

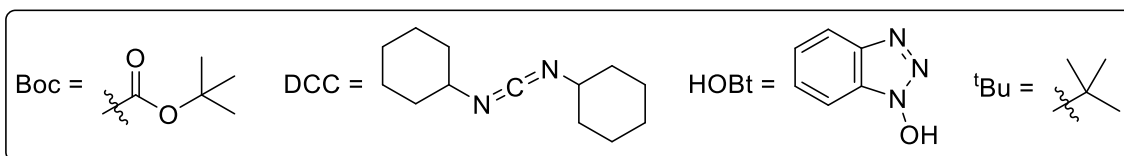
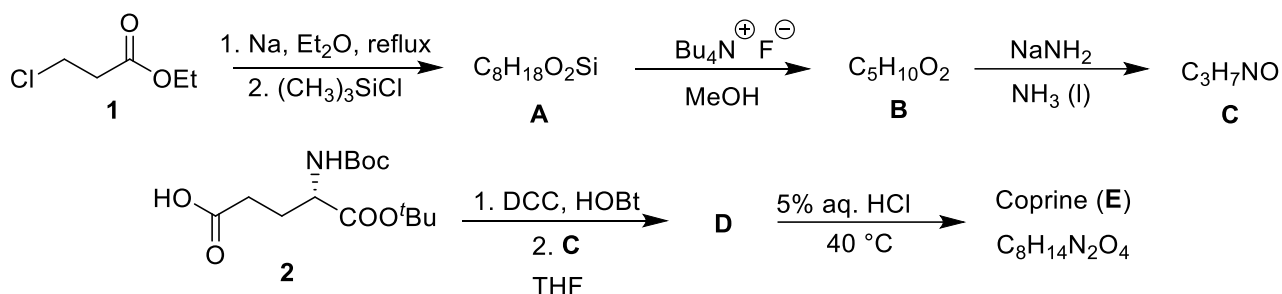


Theoretical Problem 6  7% of the total	Question	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	Total
	Points	18	4	8	3	4	12	16	3	68
	Score									

## Problem 6. Let's go mushrooming

Mushrooming belongs to Czech and Slovak traditional pastimes. While some of our mushroom species are edible, some are inedible or even poisonous.

Inky cap (*Coprinopsis atramentaria*) is considered edible and delicious. It contains a natural compound called coprine (**E**), which can be easily synthesised from ethyl 3-chloropropanoate (**1**).

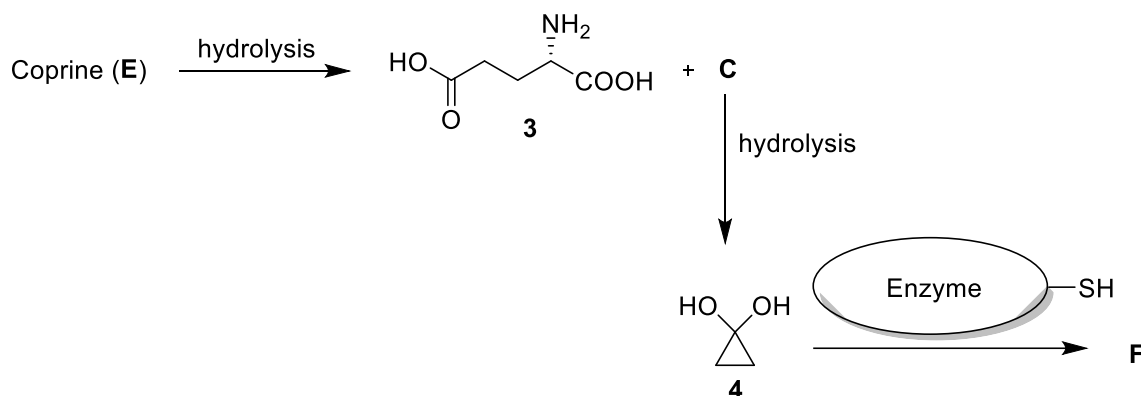


6.1 Draw the structures of compounds **A–E** including stereochemistry when necessary. *Hint: The first reaction affording compound **A** proceeds via an organometallic compound which then cyclises.*

<b>A</b>	<b>B</b>	<b>C</b>
<b>D</b>		<b>E</b>

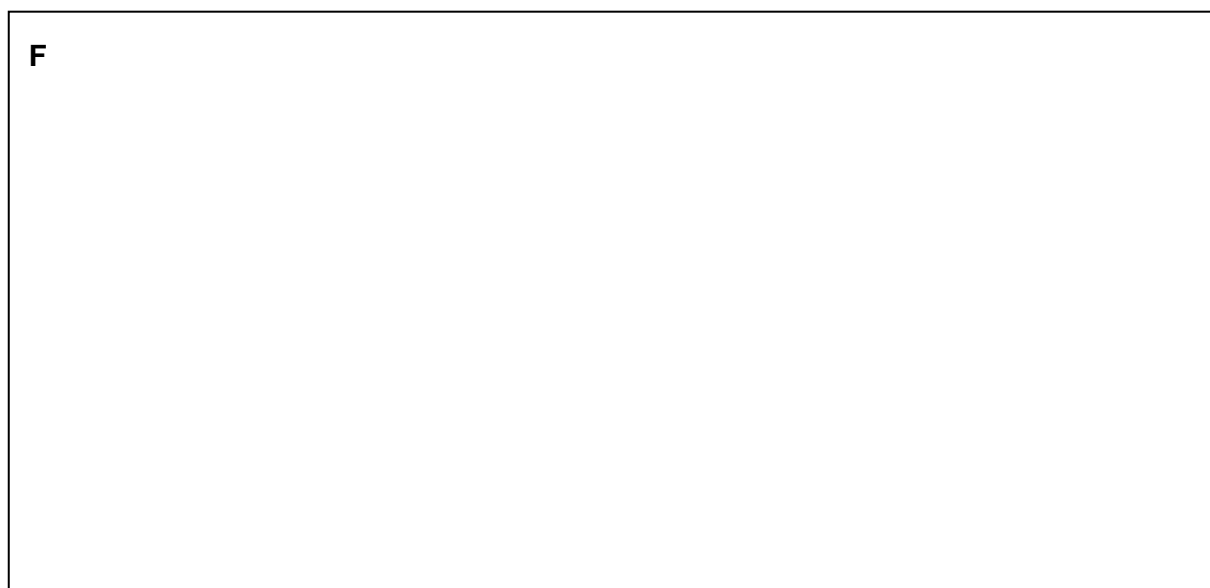


In the human body, coprine undergoes hydrolysis to L-glutamic acid (**3**) and compounds **C** and **4**, which are responsible for coprine's side-effects. These compounds inhibit the enzyme acetaldehyde dehydrogenase, which is involved in the metabolism of alcohol. Upon inhibition, acetaldehyde (formed by alcohol dehydrogenase) accumulates in the body, causing hangovers (called the antabuse effect). The active site of the enzyme contains a cysteine SH group, which is blocked either by compound **C** or **4**.

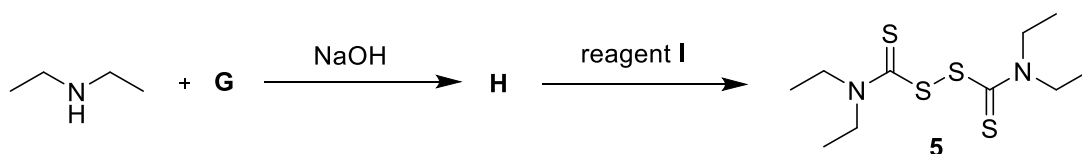


Enzyme = acetaldehyde dehydrogenase

6.2 Using the pictogram for acetaldehyde dehydrogenase above, draw the structure **F**, of the enzyme inhibited by compound **4**.



The antabuse effect was named after antabuse (**5**), the most well-known drug for alcohol-addiction treatment. This drug can be synthesised according to the following scheme.



6.3 Draw the structures of compounds **G** and **H**. *Hint: Compound **H** contains five carbon atoms.*

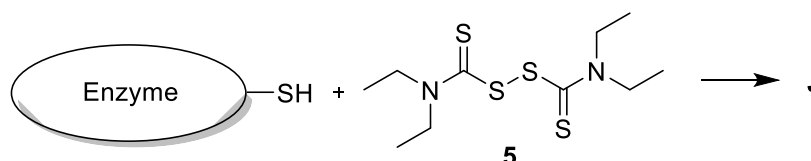


<b>G</b>	<b>H</b>
----------	----------

6.4 Mark all possible alternatives for reagent **I** from the following list.

- |  |  |
|--|--|
| <input type="checkbox"/> <i>m</i> -chloroperbenzoic acid ( <i>m</i> CPBA)  | <input type="checkbox"/> diluted H <sub>2</sub> O <sub>2</sub>           |
| <input type="checkbox"/> Zn/CH <sub>3</sub> COOH                           | <input type="checkbox"/> NaBH <sub>4</sub>                               |
| <input type="checkbox"/> I <sub>2</sub>                                    | <input type="checkbox"/> hot concentrated H <sub>2</sub> SO <sub>4</sub> |
| <input type="checkbox"/> K <sub>2</sub> CO <sub>3</sub> , H <sub>2</sub> O | <input type="checkbox"/> AlCl <sub>3</sub>                               |

The way antabuse inhibits acetaldehyde dehydrogenase is similar to the effect of compounds **C** and **4**.

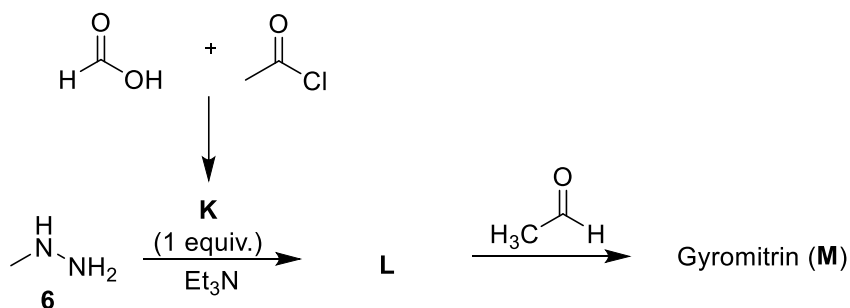


Enzyme = acetaldehyde dehydrogenase

6.5 Using the pictogram for acetaldehyde dehydrogenase above, draw the structure **J** of the enzyme inhibited by antabuse (**5**). *Hint: Three sulfur atoms should be in the structure.*

**J**

False morel (*Gyromitra esculenta*) is another interesting mushroom. Although it was considered edible in the past (*esculentus* means edible in Latin), this mushroom is poisonous due to the content of gyromitrin (**M**). This natural compound can be prepared from *N*-methylhydrazine (**6**):



6.6 Draw the structures of compounds **K–M**.

<b>K</b>	<b>L</b>	<b>M</b>
----------	----------	----------

In the human body, gyromitrin (**M**) hydrolyses and provides *N*-methylhydrazine (**6**), which is strongly hepatotoxic. Gyromitrin (**M**) hydrolyses in the acidic environment in the human stomach where both its amide and imine groups are hydrolysed.

Let us focus on the hydrolysis of the amide moiety within the gyromitrin molecule. The vibrational wavenumber of the stretching mode of the relevant C–N bond is  $1293.0 \text{ cm}^{-1}$  and the potential energy surface does not significantly alter in shape with isotopic substitution.

6.7 Calculate the highest possible hypothetical kinetic isotope effect at the temperature of the human body,  $37 \text{ }^\circ\text{C}$ , for the given hydrolysis reaction, assuming that both relevant nitrogen and carbon atoms were simultaneously substituted,  $^{14}\text{N}$  with the  $^{15}\text{N}$  isotope and  $^{12}\text{C}$  with the  $^{13}\text{C}$  isotope. Consider that only the zero-point vibrational energy affects the rate constants. Assume that the molar masses of all isotopes are integers. In all further steps consider five significant digits.



6.8 After making these isotopic changes, the rates of hydrolysis are not significantly different. Which of the following is most likely the rate determining step?

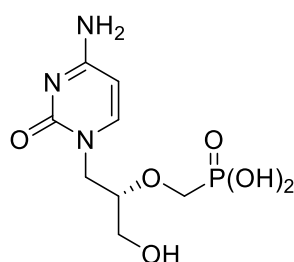
- Nucleophilic attack of water on a protonated amidic moiety
- C–N bond cleavage
- Protonation of the gyromitrin molecule



Theoretical Problem 7	Question	7.1	7.2	7.3	7.4	7.5	7.6	Total
	Points	10	6	15	9	11	6	57
7% of the total	Score							

## Problem 7. Cidofovir

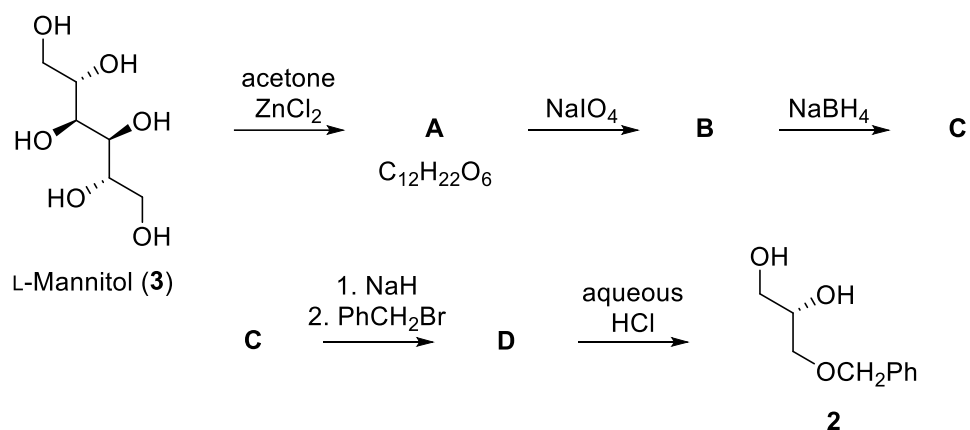
Cidofovir (**1**), originally designed and prepared by the group of Professor Holy in former Czechoslovakia, is a nucleotide analogue with antiviral activity. It is used to treat viral infections, mostly in patients with AIDS.



Cidofovir (**1**)

The key intermediate in the synthesis of cidofovir is optically pure diol **2**, which can be prepared from L-mannitol (**3**). [See scheme overleaf]





7.1 Draw the structures of compounds **A–D**, including stereochemistry. One molecule of **A** produces two molecules of **B**.

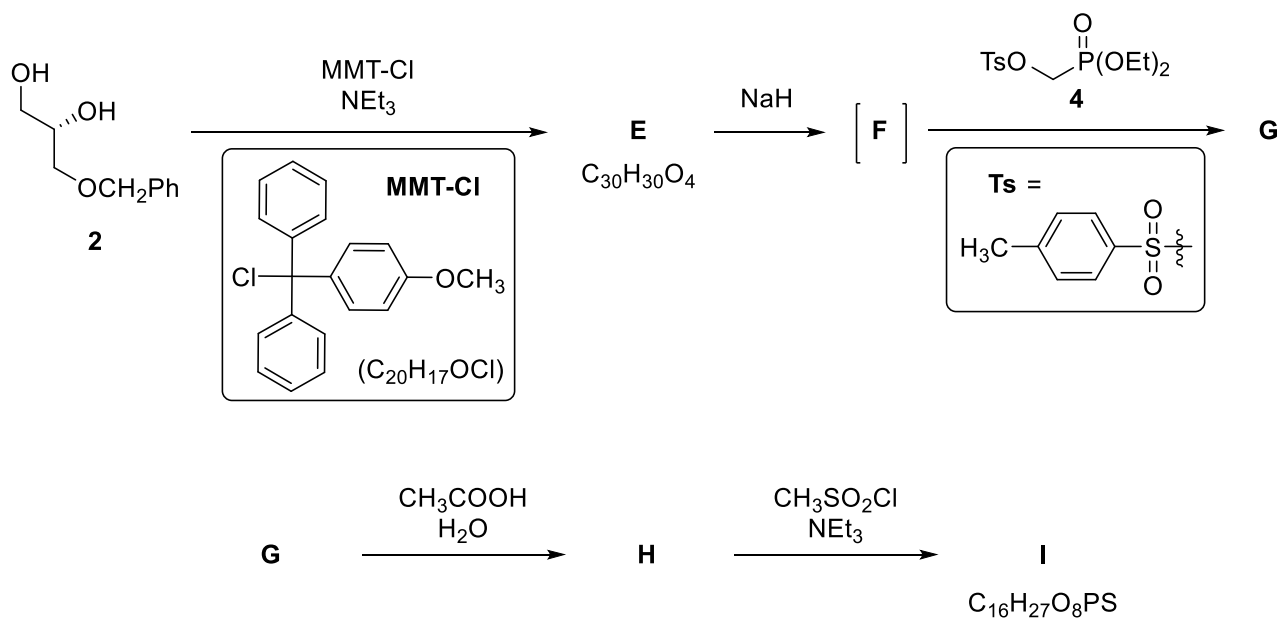
<b>A</b>	<b>B</b>
<b>C</b>	<b>D</b>



- 7.2 Draw the structures of all alternative stereoisomers of compound **3** which, if used in the same reaction sequence, give exclusively product **2**.



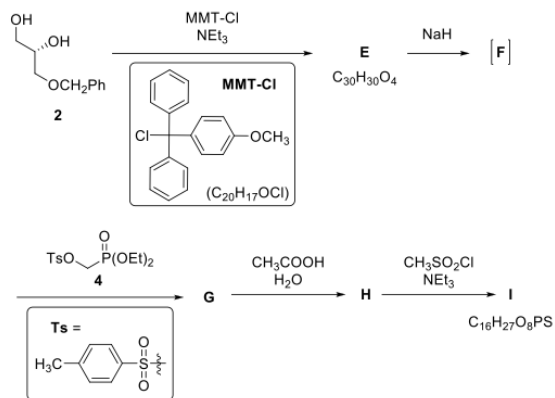
Diol **2** is further modified to provide compound **I**. The synthesis of phosphonate **4** used to convert compound **F** to **G** will be discussed later.





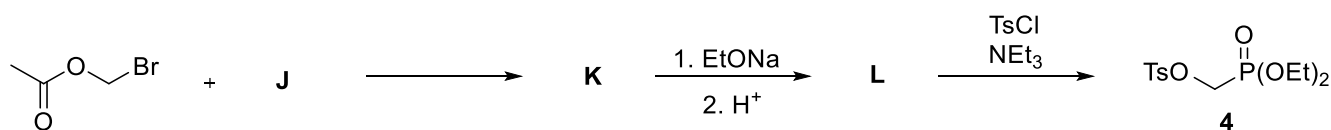
- 7.3 Draw the structures of compounds **E–I**, including stereochemistry. Use the abbreviation MMT for the (4-methoxyphenyl)diphenylmethyl group.

The same scheme as on the previous page, for easier orientation

**E** $\text{C}_{30}\text{H}_{30}\text{O}_4$ **F****G****H****I** $\text{C}_{16}\text{H}_{27}\text{O}_8\text{PS}$



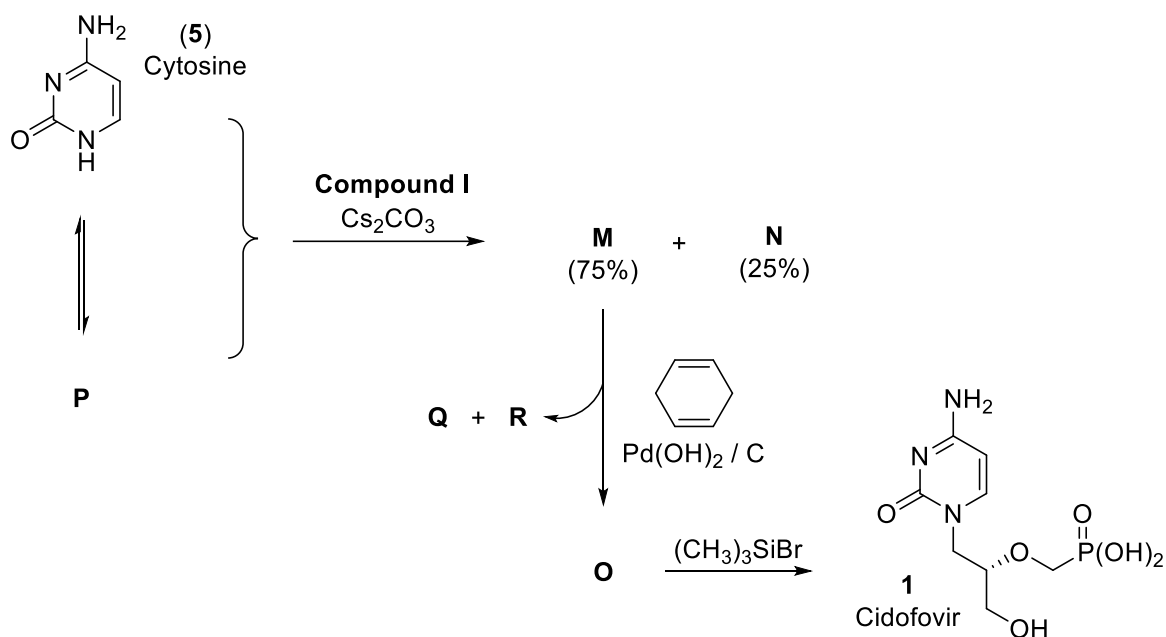
Phosphonate **4** can be prepared according to the following scheme:



7.4 Draw the structures of compounds **J–L**.

<b>J</b>	<b>K</b>
<b>L</b>	

The reaction of **I** (from question 7.3) with cytosine (**5**) leads to a 3:1 mixture of isomeric compounds **M** and **N**. The formation of these two products may be understood by realising that cytosine (**5**) can also exist as an aromatic tautomer **P**. The reaction of **M** with cyclohexa-1,4-diene and palladium hydroxide on carbon leads to compound **O**. The phosphonic ester moiety in compound **O** reacts with bromotrimethylsilane to provide cidofovir (**1**).



- 7.5 Draw the structures of the two isomers **M**, **N**, and of compound **O**, including stereochemistry, and the structure of the aromatic tautomer **P** of cytosine (**5**). The transformation of **M** to **O** is the removal of a protecting group.

<b>M</b> (75%)	<b>N</b> (25%)



<b>O</b>	<b>P</b>
----------	----------

7.6 Draw the structures of the two simple organic side products **Q** and **R** formed during the conversion of **M** to **O**.

<b>Q</b> from cyclohexadiene	<b>R</b> from the protecting group
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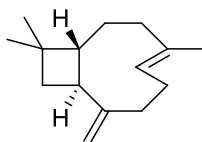


Theoretical Problem 8  9% of the total	Question	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	Total
	Points	14	14	2	16	6	8	9	6	<b>75</b>
	Score									

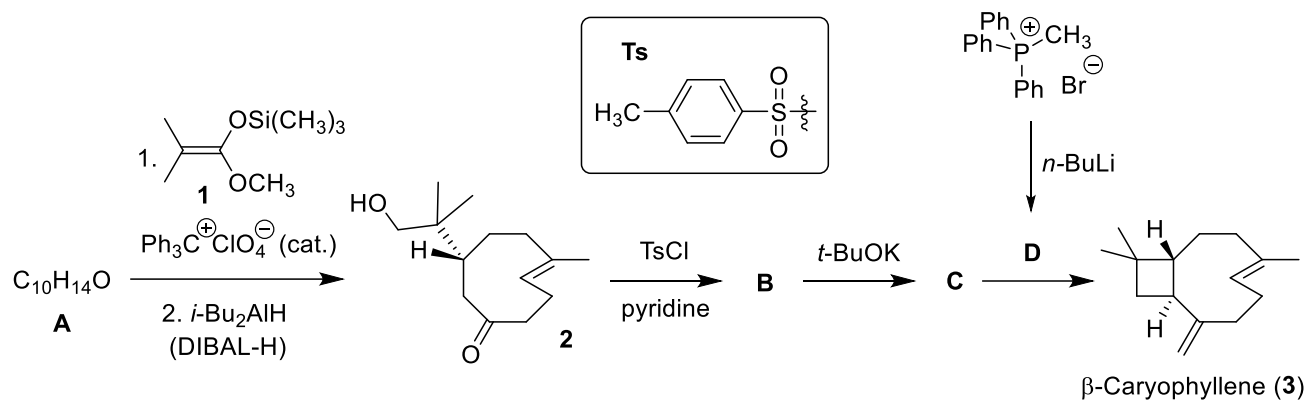
## Problem 8. Caryophyllene

$\beta$ -Caryophyllene (**3**) is a naturally occurring sesquiterpene present in clove tree and in some traditional Czech and Slovak plants, such as the hop plant or small-leaved linden.

The synthesis of  $\beta$ -caryophyllene starts from a single enantiomer of dienone **A**. The reaction of **A** with silyl ketene acetal **1**, followed by immediate reduction and aqueous work-up, produces ketone **2**. This intermediate then undergoes reaction with tosyl chloride, providing **B**. Basic cyclisation of this compound produces **C**. Finally, the reaction of **C** with ylid **D** provides  $\beta$ -caryophyllene.



$\beta$ -Caryophyllene (**3**)



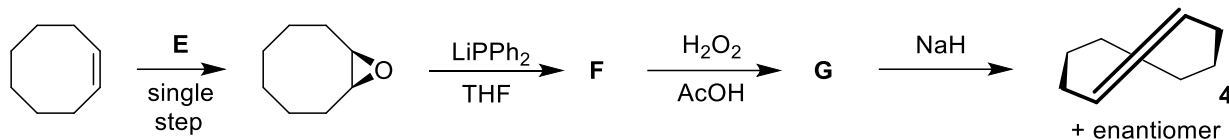
8.1 Draw the structures of compounds **A–D**, including the appropriate stereochemistry. *Hint: In transformation **A**  $\rightarrow$  **2**, the silyl ketene acetal acts as a nucleophile.*

<p><b>A</b> <math>C_{10}H_{14}O</math></p>	<p><b>B</b></p>
<p><b>C</b></p>	<p><b>D</b></p>





Due to the large ring size, both compounds **2** and **3** are stable, even though they contain a double bond in the *trans* configuration. *trans*-Cyclooctene (**4**) is the smallest ring that can accommodate a *trans* double bond. It can be prepared according to the following scheme:

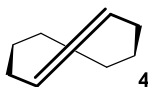


8.2 Draw the structures of reagent **E** and intermediates **F** and **G**, including the appropriate stereochemistry. For **F** and **G**, tick the box indicating the stereochemical outcome.

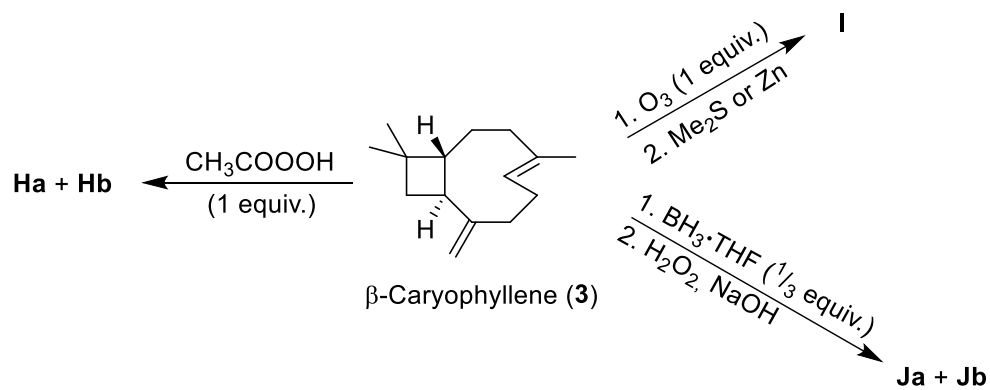
<b>E</b>	<b>F</b>          <input type="checkbox"/> achiral <input type="checkbox"/> single enantiomer <input type="checkbox"/> racemic mixture <input type="checkbox"/> mixture of diastereoisomers
<b>G</b>          <input type="checkbox"/> achiral <input type="checkbox"/> single enantiomer <input type="checkbox"/> racemic mixture <input type="checkbox"/> mixture of diastereoisomers	



8.3 Draw the structure of the enantiomer of cycloalkene **4**.



The two double bonds in  $\beta$ -caryophyllene display different reactivity: the double bond in the ring (endocyclic) is more reactive than the other one (exocyclic) due to the ring strain.



8.4 Draw the structures of compounds **Ha + Hb**, **I** and **Ja + Jb**, including the appropriate stereochemistry. *Hint: **Ha + Hb** and **Ja + Jb** are pairs of diastereomers.*



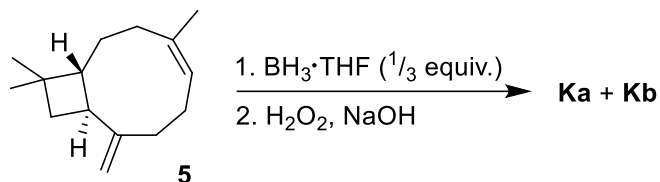
**Ha + Hb**

**I**

**Ja + Jb**



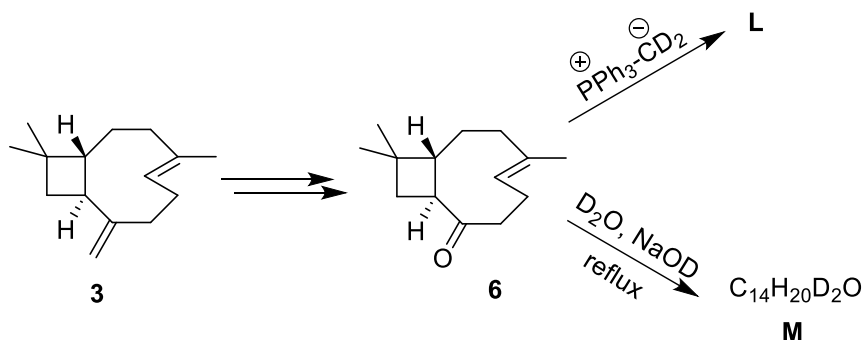
Interestingly, the reactivity of the double bonds is reversed when isocaryophyllene (**5**) is used instead of  $\beta$ -caryophyllene (**3**).



8.5 Draw the structures of compounds **Ka** and **Kb**. *Hint: **Ka** + **Kb** are a pair of diastereomers.*



Isotope-labelled compounds are invaluable tools for reaction mechanism investigation, structure determination, and mass or NMR spectroscopy studies. Let us have a look at the synthesis of some labelled analogues of  $\beta$ -caryophyllene.

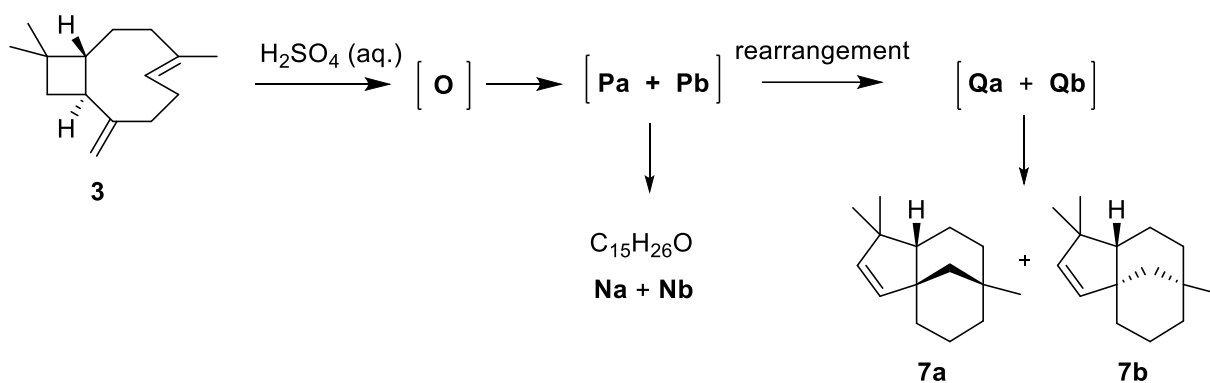


8.6 Draw the structures of compounds **L** and **M**, including the appropriate stereochemistry.



<b>L</b>	<b>M</b> <span style="float: right;">C<sub>14</sub>H<sub>20</sub>D<sub>2</sub>O</span>
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$\beta$ -Caryophyllene (**3**) undergoes acid-catalysed cyclisation, which leads to a complex mixture of products. Among them, the pair of diastereomers **Na** + **Nb** and the pair of diastereomers **7a** + **7b** are the most abundant. The reaction starts with protonation of the more reactive internal double bond affording cation **O**. This cyclises without the cleavage of a carbon-carbon single bond to yield diastereomeric tricyclic cations **Pa** and **Pb**, which undergo hydration to give the target alcohols **Na** and **Nb**. Alternatively, the cations **Pa** and **Pb** rearrange with the cleavage of a carbon-carbon single bond to cations **Qa** and **Qb**, which deprotonate to compounds **7a** and **7b**.



8.7 Draw the structures, including the appropriate stereochemistry, of the **three** intermediates **O**, **Pa**, **Qa** leading to the diastereomer **7a**.



<b>O</b>	<b>Pa</b>
<b>Qa</b>	

8.8 Draw the structures of diastereomers **Na + Nb**.

<b>Na + Nb</b>	$C_{15}H_{26}O$
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