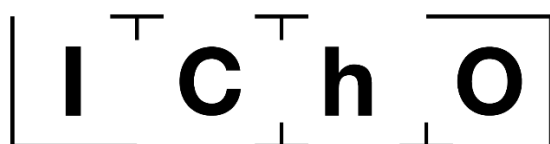


THEORETICAL EXAM




**51st — International
Chemistry Olympiad
France — Paris — 2019**

Making science together!

2019-07-26



 <p>Liberté • Égalité • Fraternité RÉPUBLIQUE FRANÇAISE</p>	<p>MINISTÈRE DE L'ÉDUCATION NATIONALE ET DE LA JEUNESSE</p>	<p>MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR, DE LA RECHERCHE ET DE L'INNOVATION</p>
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General instructions

- This theoretical exam booklet contains 60 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.
- If you need scratch paper, use the backside of the exam sheets. Remember that nothing outside the designed areas will be graded.
- 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 corresponding IChO card. An exam supervisor will come to accompany you.
- For multiple-choice questions: if you want to change your answer, fill the answer box completely and then make a new empty answer box next to it.
- 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, then wait at your seat. The exam supervisor will come to seal the envelope in front of you and collect it.

GOOD LUCK!

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Physical constants and equations

In these tasks, we assume the activities of all aqueous species to be well approximated by their respective concentration in mol L⁻¹. To further simplify formulas and expressions, the standard concentration $c^\circ = 1 \text{ mol L}^{-1}$ is omitted.

Avogadro's constant:	$N_A = 6.022 \cdot 10^{23} \text{ mol}^{-1}$
Universal gas constant:	$R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$
Standard pressure:	$p^\circ = 1 \text{ bar} = 10^5 \text{ Pa}$
Atmospheric pressure:	$P_{\text{atm}} = 1 \text{ atm} = 1.013 \text{ bar} = 1.013 \cdot 10^5 \text{ Pa}$
Zero of the Celsius scale:	273.15 K
Faraday constant:	$F = 9.6485 \cdot 10^4 \text{ C mol}^{-1}$
Watt:	1 W = 1 J s ⁻¹
Kilowatt hour:	1 kWh = 3.6 · 10 ⁶ J
Planck constant:	$h = 6.6261 \cdot 10^{-34} \text{ J s}$
Speed of light in vacuum:	$c = 2.998 \cdot 10^8 \text{ m s}^{-1}$
Elementary charge:	$e = 1.6022 \cdot 10^{-19} \text{ C}$
Electron-volt	1 eV = 1.6022 · 10 ⁻¹⁹ J
Electrical power:	$P = \Delta E \times I$
Power efficiency:	$\eta = P_{\text{obtained}}/P_{\text{applied}}$
Planck-Einstein relation:	$E = hc/\lambda = h \nu$
Ideal gas equation:	$pV = nRT$
Gibbs free energy:	$G = H - TS$

Reaction quotient Q for a reaction
 $a \text{ A(aq)} + b \text{ B(aq)} = c \text{ C(aq)} + d \text{ D(aq)}$:

$$Q = \frac{[\text{C}]^c [\text{D}]^d}{[\text{A}]^a [\text{B}]^b}$$

Henderson–Hasselbalch equation:

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

Nernst–Peterson equation:

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

where Q is the reaction quotient
of the reduction half-reaction

$$\text{at } T = 298 \text{ K, } \frac{RT}{F} \ln 10 \approx 0.059 \text{ V}$$

Beer–Lambert law:

$$A = \epsilon l c$$

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:

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

Half-life for a first order process:

$$\frac{\ln 2}{k}$$

Number average molar mass M_n :

$$M_n = \frac{\sum_i N_i M_i}{\sum_i N_i}$$

Mass average molar mass M_w :

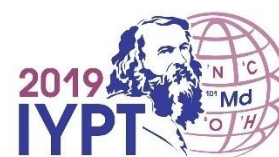
$$M_w = \frac{\sum_i N_i M_i^2}{\sum_i N_i M_i}$$

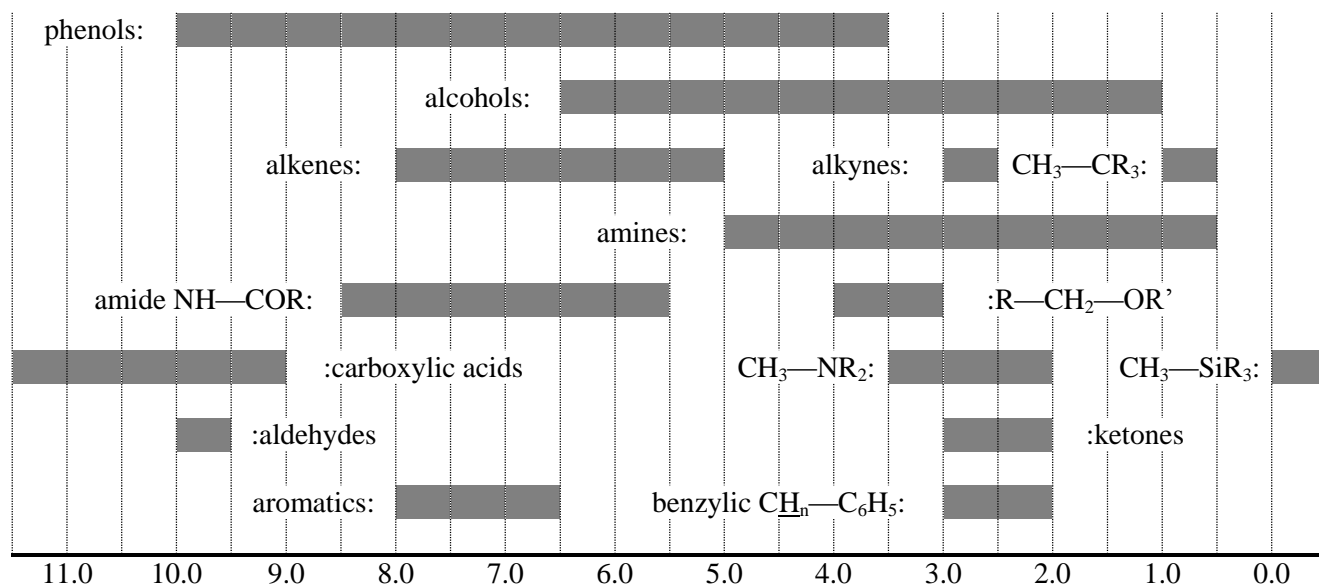
Polydispersity index I_p :

$$I_p = \frac{M_w}{M_n}$$

Periodic table

1																												18				
1 H 1.008																												2 He 4.003				
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18															
11 Na 22.99	12 Mg 24.31	3	4	5	6	7	8	9	10	11	12	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95															
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.63	33 As 74.92	34 Se 78.97	35 Br 79.90	36 Kr 83.80															
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc -	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3															
55 Cs 132.9	56 Ba 137.3	57-71	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po -	85 At -	86 Rn -															
87 Fr -	88 Ra -	89-103	104 Rf -	105 Db -	106 Sg -	107 Bh -	108 Hs -	109 Mt -	110 Ds -	111 Rg -	112 Cn -	113 Nh -	114 Fl -	115 Mc -	116 Lv -	117 Ts -	118 Og -															
																		57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm -	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
																		89 Ac -	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np -	94 Pu -	95 Am -	96 Cm -	97 Bk -	98 Cf -	99 Es -	100 Fm -	101 Md -	102 No -	103 Lr -



^1H NMR**Chemical shifts of hydrogen (in ppm / TMS)****H-H coupling constants (in Hz)**

Hydrogen type	$ J_{ab} $ (Hz)
$\text{R}_2\text{CH}_a\text{H}_b$	4-20
$\text{R}_2\text{H}_a\text{C—CR}_2\text{H}_b$	2-12 if free rotation: 6-8 ax-ax (cyclohexane): 8-12 ax-eq or eq-eq (cyclohexane): 2-5
$\text{R}_2\text{H}_a\text{C—CR}_2\text{—CR}_2\text{H}_b$	if free rotation: < 0.1 otherwise (rigid): 1-8
$\text{RH}_a\text{C=CRH}_b$	<i>cis</i> : 7-12 <i>trans</i> : 12-18
$\text{R}_2\text{C=CH}_a\text{H}_b$	0.5-3
$\text{H}_a(\text{CO})\text{—CR}_2\text{H}_b$	1-3
$\text{RH}_a\text{C=CR—CR}_2\text{H}_b$	0.5-2.5

eq = equatorial, ax = axial

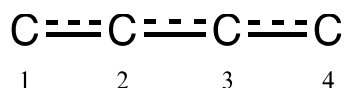
IR spectroscopy table

Vibrational mode	σ (cm ⁻¹)	Intensity
alcohol O—H (stretching)	3600-3200	strong
carboxylic acid O—H (stretching)	3600-2500	strong
N—H (stretching)	3500-3350	strong
\equiv C—H (stretching)	3300	strong
=C—H (stretching)	3100-3000	weak
C—H (stretching)	2950-2840	weak
—(CO)—H (stretching)	2900-2800	weak
C \equiv N (stretching)	2250	strong
C=C (stretching)	2260-2100	variable
aldehyde C=O (stretching)	1740-1720	strong
anhydride C=O (stretching)	1840-1800; 1780-1740	weak; strong
ester C=O (stretching)	1750-1720	strong
ketone C=O (stretching)	1745-1715	strong
amide C=O (stretching)	1700-1500	strong
alkene C=C (stretching)	1680-1600	weak
aromatic C=C (stretching)	1600-1400	weak
CH ₂ (bending)	1480-1440	medium
CH ₃ (bending)	1465-1440; 1390-1365	medium
C—O—C (stretching)	1250-1050	strong
C—OH (stretching)	1200-1020	strong
NO ₂ (stretching)	1600-1500; 1400-1300	strong

Problem T1 6%	Question	1	2	3	4	5	6	7	8	9	10	11	Total
	Points	3	4	4	2	3	2	2	4.5	2.5	3	3	33
	Score												

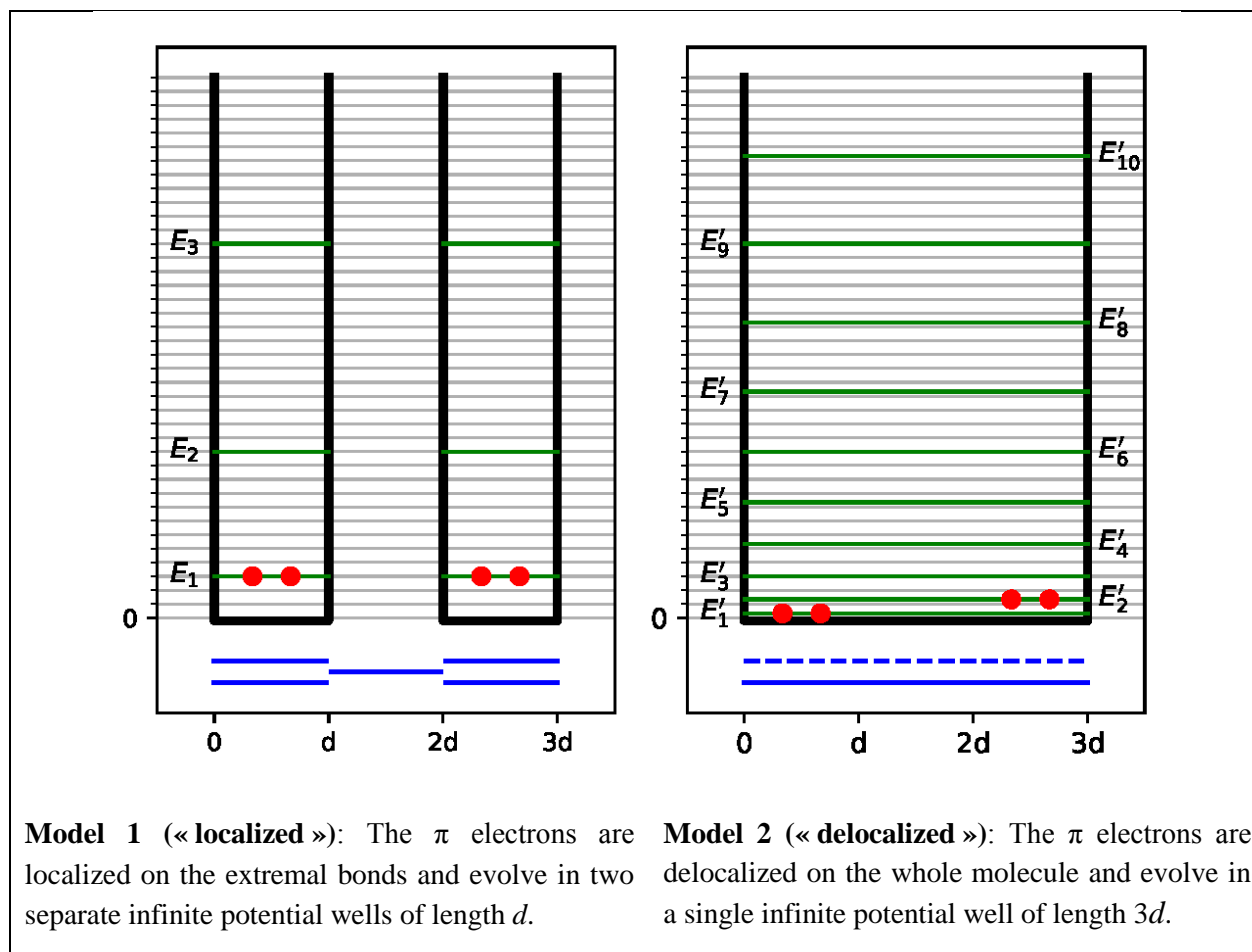
Problem T1: Infinite well and butadiene

The buta-1,3-diene molecule is often written $\text{CH}_2=\text{CH}-\text{CH}=\text{CH}_2$, with alternating single and double bonds. Nevertheless, its chemical reactivity is not consistent with this description and the π electrons are better described by a distribution along the three bonds:



This system can be modeled as a 1D box (*i.e.* infinite well) where the electrons are free. The energy of an electron in an infinite well of length L is: $E_n = \frac{n^2 h^2}{8m_e L^2}$, where n is a **non-zero** positive integer.

- Two different models are studied. **Sketch** at least the three lowest-energy levels E_n **for each model** in the respective diagrams, showing how the relative energy levels differ within and between models.



- +1 point if the gap between levels increases with increasing energy in model 1
- +1 point if the gap between levels increases with increasing energy in model 2
- +1 point if the gap of model 1 is larger than the gap of model 2

Total: 3 points

2. **Place** the π electrons for model 1 in the previous diagrams and **express** the total energy of the π system in model 1, as a function of h , m_e and d .

- + 1 point for two electrons for each level
- + 1 point if four electrons in total
- + 1 point if they fill levels by increasing energy

$$E(1) = 2 \times 2E_1 = \frac{h^2}{2m_e d^2} \quad (1 \text{ point})$$

Total: 4 points

3. **Place** the π electrons for model 2 in the previous diagrams and **express** the total energy of the π system in model 2, as a function of h , m_e and d .

- + 1 point for two electrons for each level
- + 1 point if four electrons in total
- + 1 point if they fill levels by increasing energy

$$E(2) = 2E_1 + 2E_2 = \frac{5h^2}{36m_e d^2} \quad (1 \text{ point})$$

Total: 4 points

The conjugation energy is the total energy of the actual π system, minus the sum of the energies of ethylene molecules involving the same number of electrons.

4. **Express** the conjugation energy ΔE_c of butadiene, as a function of h , m_e and d .

$$\Delta E_c = E(2) - E(1) = -\frac{13h^2}{36m_e d^2}$$

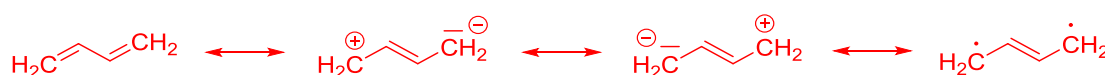
1 point for the expression $E(2) - E(1)$

1 point for consistent computation

Total: 2 points (only if consistent with Q2 and Q3)

Models 1 and 2 are too simplistic. A new model will be detailed in the following.

5. **Draw** three other resonance structures of butadiene using Lewis notation.



1 point for each acceptable resonance structure (correct charge, number of electrons, etc.).
The non-bonding electron pairs are not required.

Total: 3 points

To take into account the size of carbon atoms, model 2 is now modified into model 3, as follows:

- the new length of the well is L and is located between the abscissa 0 and L ;
- the carbon atoms are located at the abscissas $L/8$; $3L/8$; $5L/8$ and $7L/8$.

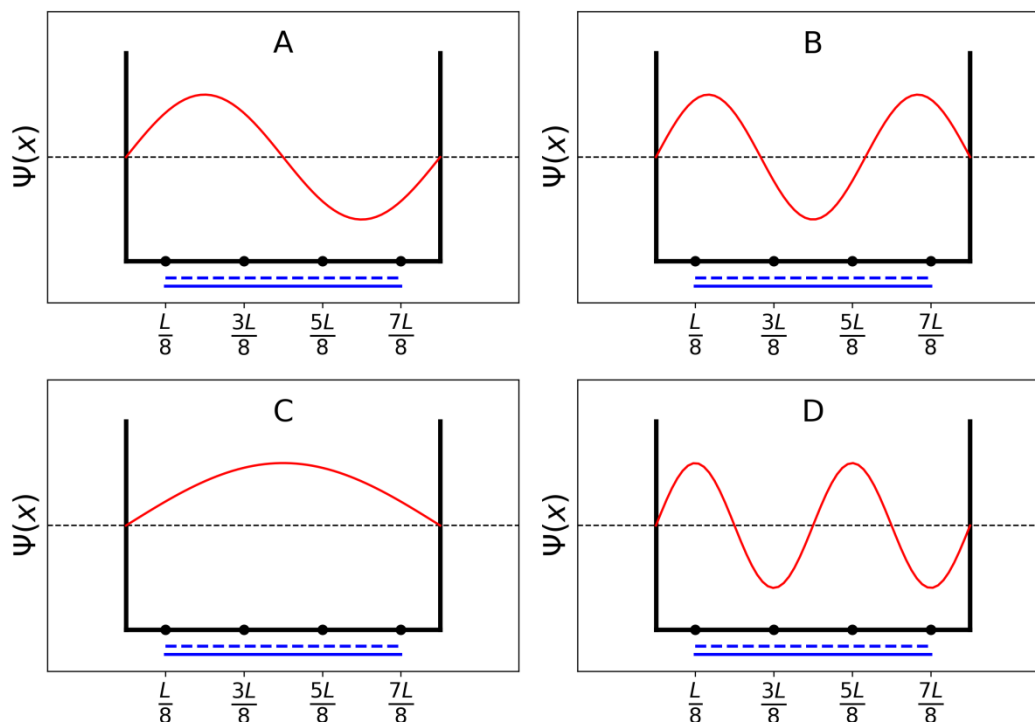
For each level n , the π wavefunction is:

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)$$

and the π electron density for a system with N π electrons is:

$$\rho(x) = 2 \sum_{i=1}^{N/2} |\psi_i(x)|^2$$

The four π wavefunctions, which correspond to the molecular orbitals of the π system, are depicted below (**arbitrary order**).



6. **Sort** the energies of the four π wavefunctions (E_A , E_B , E_C and E_D).

$E_C < E_A < E_B < E_D$

+1 point if E_C is correctly localized
 +1 point if the order is correct

Total: 2 points

7. **Give** the labels (A, B, C or D) of the orbitals that are filled with electrons in butadiene.

C and A

1 point for each orbital found correctly
 -1 if 3 orbitals given; -2 if 4 orbitals.

Total: 2 points

8. Within model 3, **give** the values of the π wavefunctions ψ_n for occupied levels at positions 0, $L/4$ and $L/2$, for $n = 1$ and $n = 2$, as a function of L .

$$\psi_1(0) = 0 \quad (0.5 \text{ point}) ; \psi_1\left(\frac{L}{4}\right) = \sqrt{\frac{1}{L}} \quad (1 \text{ point}) ; \psi_1\left(\frac{L}{2}\right) = \sqrt{\frac{2}{L}} \quad (1 \text{ point})$$

$$\psi_2(0) = 0 \quad (0.5 \text{ point}) ; \psi_2\left(\frac{L}{4}\right) = \sqrt{\frac{2}{L}} \quad (1 \text{ point}) ; \psi_2\left(\frac{L}{2}\right) = 0 \quad (0.5 \text{ point})$$

Total: 4.5 points

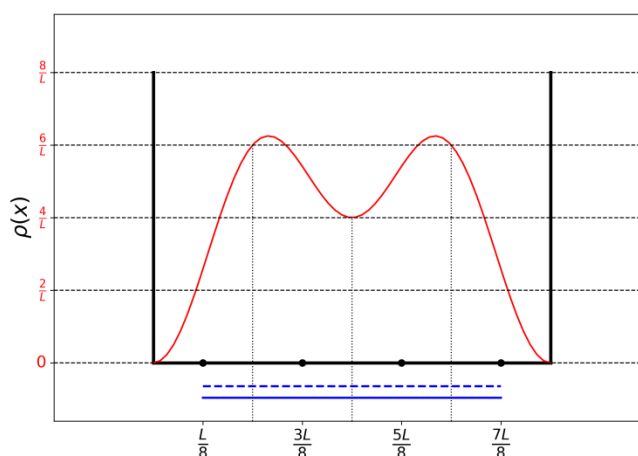
9. Within model 3, **give** the value of the π electron density at positions 0, $L/4$ and $L/2$.

$$\rho(0) = 0 ; \rho\left(\frac{L}{4}\right) = \frac{6}{L} ; \rho\left(\frac{L}{2}\right) = \frac{4}{L}$$

0.5 point for the first value, 1 point for each other calculation.

Total: 2.5 points

10. **Draw** the π electron density between 0 and L .



1 point if the graph is symmetric

1 point if values at 0, $L/4$ and $L/2$ are correctly reported from Q9

1 point if the general trend is correct

Total: 3 points

11. **Sort** the following CC bonds (B1, B2, ..., B5) by increasing length, using the symbols = or <:

B1: C1C2 in the butadiene molecule

B2: C2C3 in the butadiene molecule

B3: C3C4 in the butadiene molecule

B4: CC in the ethane molecule

B5: CC in the ethene molecule

$$B5 < B1 = B3 < B2 < B4$$

+2×0.5 points for the position of B4 and B5

+1 point for B1 = B3

+1 point for the order between B1/B3 and B2

Total: 3 points

Problem	Question	1	2	3	4	5	6	7	8	9	10	Total
T2	Points	1	4	2	3	3	6	4	1	8	2	34
7%	Score											

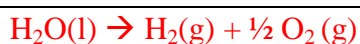
Problem T2: Hydrogen production by water-splitting

Data:

Compound	H ₂ (g)	H ₂ O(l)	H ₂ O(g)	O ₂ (g)
$\Delta_f H^\circ$ (kJ mol ⁻¹)	0	-285.8	-241.8	0
S_m° (J mol ⁻¹ K ⁻¹)	130.6	69.9	188.7	205.2

Molecular hydrogen (H₂) can be used as an alternative to carbon dioxide-emitting fuels. Hence, lowering the cost and the environmental impact of its production is a major challenge. In this field, water-splitting is a promising candidate technology.

1. **Write down** the balanced equation of liquid water splitting reaction using a stoichiometric coefficient of 1 for water.



Total: 1 point

2. Using only the provided thermodynamic data, **justify numerically** whether this reaction is thermodynamically favorable at 298 K.

Calculations:

$$\Delta_r H^\circ = 285.8 \text{ kJ mol}^{-1} \quad (1 \text{ point})$$

$$\Delta_r S^\circ = 163.3 \text{ J K}^{-1} \text{ mol}^{-1} \quad (1 \text{ point})$$

$$\text{At } 298 \text{ K, } \Delta_r G^\circ = 237.1 \text{ kJ mol}^{-1} > 0 \quad (1 \text{ point})$$

$$\text{Or } K^\circ = \exp(-\Delta_r G^\circ/RT) = 2.75 \times 10^{-42} = 10^{-41.6} \ll 1$$

Reaction thermodynamically favorable?

Yes No (1 point)

0 point if No without a numerical justification

Total: 4 points

Water splitting can be performed electrochemically using two electrodes in an acidic water bath, connected by a generator (Fig. 1). Gas bubbles are formed at both electrodes.

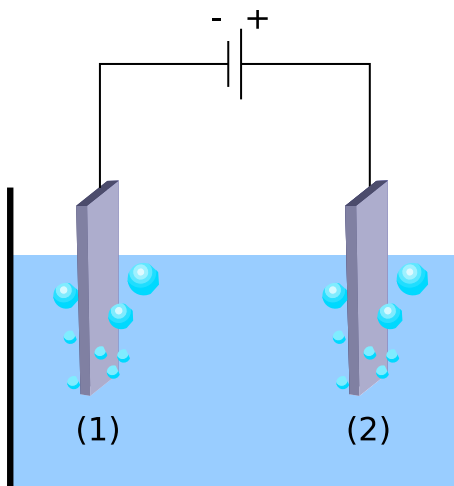
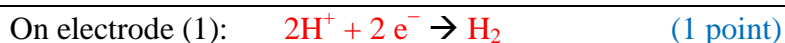


Fig. 1– Water-splitting electrochemical cell.

3. **Write down** the balanced net electrochemical half reactions occurring at each electrode.



Total: 2 points (0 point if not balanced)

4. Using only the provided thermodynamic data (or question 2), **derive** the condition on the applied voltage $\Delta E_{\text{applied}}$ between electrodes, compared to value ΔE_{th} (to **determine**), for the process to be thermodynamically favorable at 298 K, when all reactants and products are in their standard state. **Tick** the right condition and **give** the numerical value with 3 decimal places.

Calculation:

$\Delta E_{\text{applied}}$ must be $> \Delta E_{\text{th}} = \Delta_r G^\circ / 2F$

$\Delta E_{\text{th}} > \Delta_r G^\circ / 2F = 237.1 \times 10^3 / (2 \times 96485)$

(1 point)

The + sign associated to electrolysis is required

$\Delta E_{\text{applied}} = \Delta E_{\text{th}}$

$\Delta E_{\text{applied}} > \Delta E_{\text{th}}$, where $\Delta E_{\text{th}} = \dots 1.229 \dots \text{V}$

$\Delta E_{\text{applied}} < \Delta E_{\text{th}}$ (give the result with 3 decimal places)

(1 point for correct symbol, 1 point for numerical value)

Total: 3 points

If you could not calculate ΔE_{th} , the value 1.200 V can be used in the rest of the problem.

Experimentally, a higher voltage is needed to observe water splitting. For a given Pt cathode, the minimum voltage necessary to observe water splitting, ΔE_{min} , depends on the nature of the anode, as displayed in the table below:

Anode	ΔE_{min} (V)
IrO _x	1.6
NiO _x	1.7
CoO _x	1.7
Fe ₂ O ₃	1.9

The difference between ΔE_{\min} and ΔE_{th} is responsible for losses in the device.

5. **Give** the expression of the device power efficiency η_{elec} (fraction of the power used for water splitting) as a function of ΔE_{th} and ΔE_{\min} . Assuming an identical current value I , **calculate** the water electrolysis power efficiency when a Pt cathode and a Fe_2O_3 anode are used. **Give** the most efficient anode.

$$\eta_{\text{elec}} = P_{\text{eff}}/P_{\text{applied}} = \Delta E_{\text{th}}/\Delta E_{\min} \quad (1 \text{ point})$$

Power efficiency when a Pt and a Fe_2O_3 electrodes are used

$$\eta_{\text{elec}} = 1.229/1.9 = 65\% \quad (\eta_{\text{elec}} = 63\% \text{ if used } \Delta E_{\text{th}} = 1.200 \text{ V}) \quad (1 \text{ point})$$

Most efficient anode: IrO_x (1 point)

Total: 3 points

If you could not calculate η_{elec} , the value $\eta_{\text{elec}} = 75\%$ can be used in the rest of the problem.

An alternative to water electrolysis is direct photocatalytic water-splitting. It uses a semiconductor that can be activated by absorbing light.

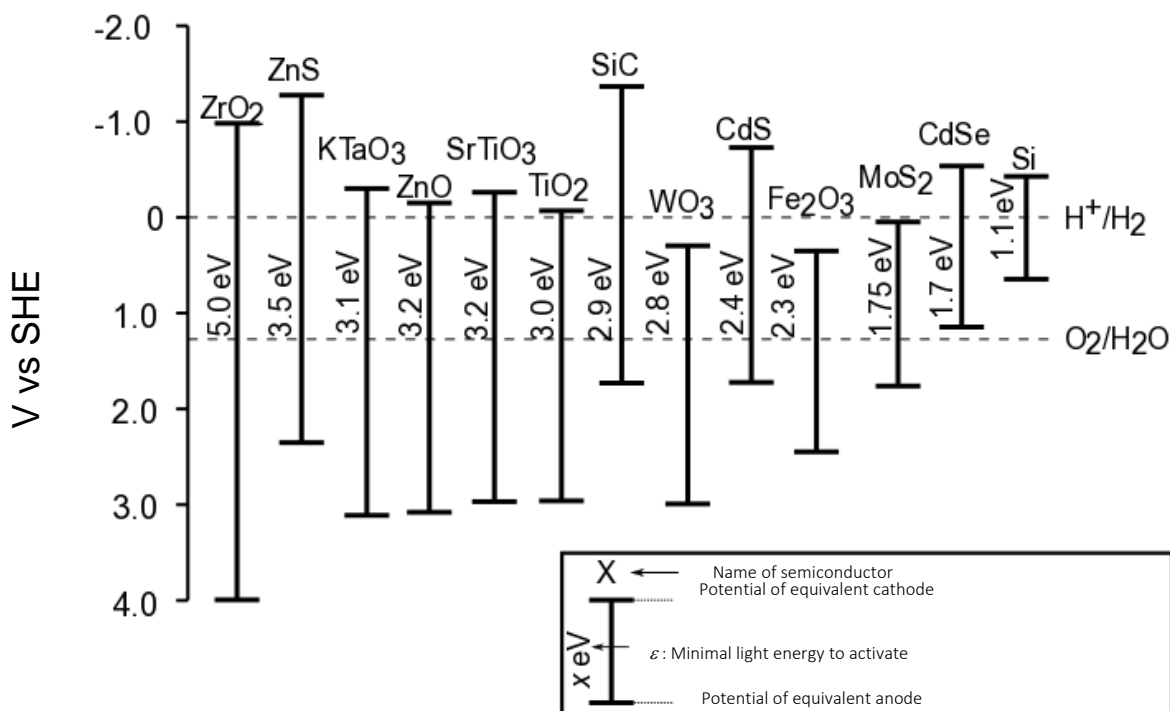


Fig. 2 – Activation condition and equivalent electrode potentials of different semiconductors. Dashed lines correspond to water oxidation and reduction potentials. SHE = Standard Hydrogen Electrode

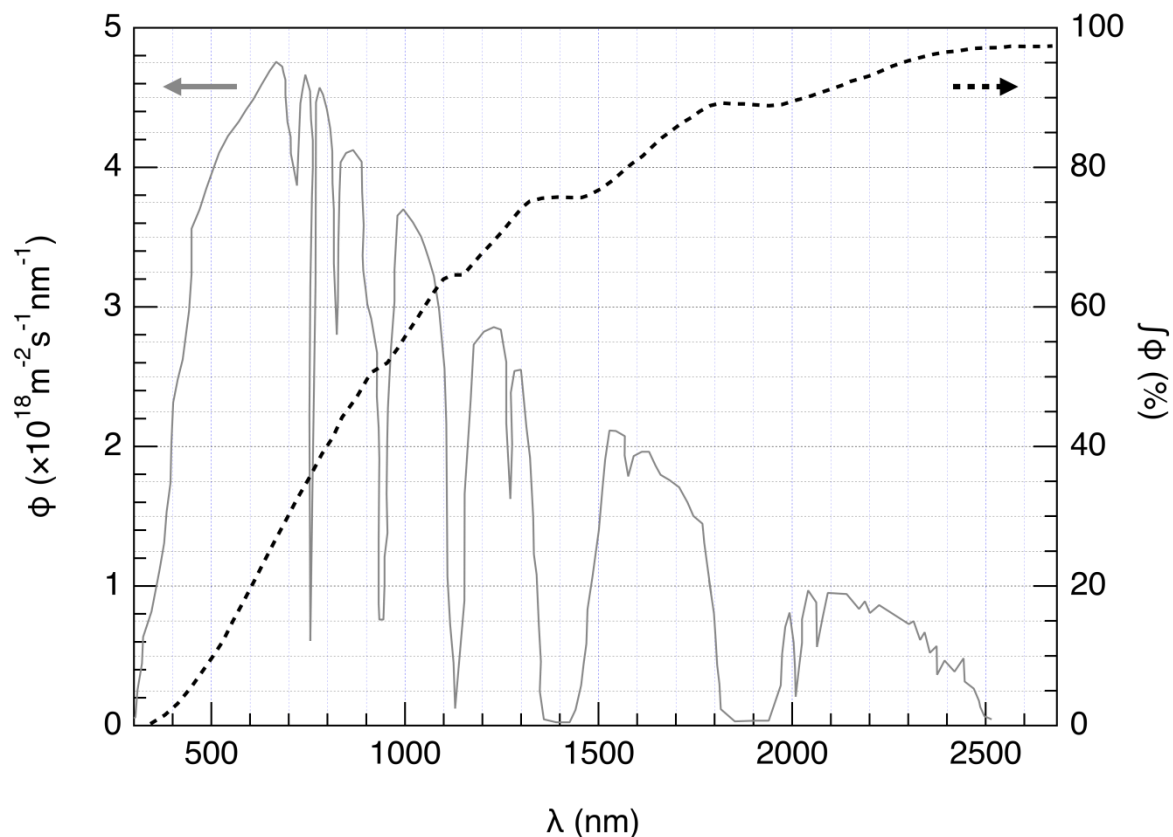


Fig. 3 – Left axis: Spectral distribution of the solar photon flux ϕ . The photon flux is the number of photons per unit area per unit time arriving on the semiconductor. Right axis and dashed line: cumulative photon flux (i.e. fraction of the photon flux with smaller wavelength).

6. **Estimate** the fraction of the solar photon flux that can activate the following semiconductors: TiO_2 , CdS, Si. **State** explicitly the equations and units used for the computation.

Explanation / calculation:

$$E(J) = hc / \lambda \quad \text{so } E(\text{eV}) = hc / \lambda e$$

$$\lambda = (hc/e)(1/E) = 1.240 \cdot 10^{-6} / E \text{ (m)} \quad \lambda = 1240 / E \text{ (nm)}$$

$$\text{TiO}_2 \quad \lambda = 1240 / 3.0 = 413 \text{ nm} \quad (1 \text{ point})$$

$$\text{CdS} \quad \lambda = 1240 / 2.4 = 517 \text{ nm} \quad (1 \text{ point})$$

$$\text{Si} \quad \lambda = 1240 / 1.1 = 1127 \text{ nm} \quad (1 \text{ point})$$

Graphical determination of % according to the λ values. (1 point for each value)

Total: 6 points

	Approximate fraction
TiO_2	1%
CdS	15%
Si	65%

The activation of the semi-conductor results in a modification of the surface potentials, so that it can be seen as two electrodes of different potentials.

7. Using the data in Fig 2, **choose** the semiconductor(s) in the following list that, once activated, can play both roles of anode and cathode for water-splitting reaction.

<input checked="" type="checkbox"/> ZrO ₂	<input checked="" type="checkbox"/> ZnO	<input checked="" type="checkbox"/> TiO ₂	<input type="checkbox"/> WO ₃
<input checked="" type="checkbox"/> CdS	<input type="checkbox"/> Fe ₂ O ₃	<input type="checkbox"/> CdSe	<input type="checkbox"/> Si

(1 point for each correct answer, -1 point for each error. No negative points in total.)

Total: 4 points

8. **Give** the semiconductor that, used as both cathode and anode, is expected to be the most efficient for water splitting upon a given solar shining.

CdS

Total: 1 point

The evolution of H₂ and O₂ when a semiconductor is irradiated by simulated solar light at $T = 25\text{ }^{\circ}\text{C}$ at p_{atm} was recently studied. Using an incident power light of $P = 1.0\text{ kW m}^{-2}$ and a photoelectrode with a $S = 16\text{ mm}^2$ surface, the production of $V = 0.37\text{ cm}^3$ of H₂(g) was measured after $\Delta t = 1$ hour of reaction.

9. **Calculate** the power efficiency η_{direct} of the conversion.

Calculation:

Energy received from light.
 $E = P \times S \times \Delta t = 10^3 \times 3600 \times 16 \times 10^{-6} = 58\text{ J}$ (2 points)

Energy contained in H₂
 $n(\text{H}_2) = pV/RT = 1.013 \times 10^5 \times 0.37 \times 10^{-6} / (8.314 \times 298) = 15\text{ }\mu\text{mol}$ (2 points)
 $n(\text{H}_2) \times \Delta_r G^\circ = 3.6\text{ J}$ (2 points)

Power efficiency $\eta_{\text{direct}} = 3.6/58 = 6.2\%$ (2 points)

$\eta_{\text{direct}} = 6.2\%$

Total: 8 points

If you could not calculate η_{direct} , the value $\eta_{\text{direct}} = 10\%$ can be used in the rest of the problem.

Two modes of converting solar energy to hydrogen can thus be compared: direct photocatalysis, and indirect photo-electrolysis combining a photovoltaic panel with an electrolyzer. The efficiency of photovoltaic panels on the market is around $\eta_{\text{panels}} = 20\%$.

10. **Compare** the power efficiencies of the two modes, η_{direct} and η_{indirect} , using Fe₂O₃ and Pt electrodes for the electrolysis.

Calculation:

Direct photocatalysis: $\eta_{\text{direct}} = 6.2 \%$

Indirect photocatalysis:

$$\eta_{\text{indirect}} = 0.65 \times 0.20 = 13 \%$$

(1 point)

(if calculated with the given values: $0.75 \times 0.20 = 12 \%$)

Indirect photo-electrolysis is the most efficient:

$\eta_{\text{direct}} > \eta_{\text{indirect}}$

$\eta_{\text{direct}} \approx \eta_{\text{indirect}}$

$\eta_{\text{direct}} < \eta_{\text{indirect}}$

(1 point)

(0.5 point if the data to conclude are not specified)

Total: 2 points

Problem T3 5%	Question	1	2	3	4	5	6	7	8	9	10	11	12	Total
	Points	1	3	3	3	4	2	7	2	2	3	4	6	40
	Score													

Problem T3: About silver chloride

Data at 298 K:

$$pK_{s1}(\text{AgCl}) = 9.7 ; pK_{s2}(\text{Ag}_2\text{CrO}_4) = 12$$

Formation constant of the complex $[\text{Ag}(\text{NH}_3)_n]^+$: $\beta_n = 10^{7.2}$

Potentials against the standard hydrogen electrode:

$$\text{Standard potential of } \text{Ag}^+/\text{Ag}(\text{s}): E^\circ(\text{Ag}^+/\text{Ag}(\text{s})) = 0.80 \text{ V}$$

$$\text{Apparent potential of } \text{O}_2(\text{aq})/\text{HO}^-(\text{aq}) \text{ (in seawater): } E'(\text{O}_2(\text{aq})/\text{HO}^-(\text{aq})) = 0.75 \text{ V}$$

Part A: Quotes from a chemistry lesson by Louis Joseph Gay-Lussac

The following quotes from a chemistry lesson by Louis Joseph Gay-Lussac (French chemist and physicist, 1778–1850) deal with some properties of silver chloride.

Quote A: “I will now talk about silver chloride, a milk-white solid. It is easily obtained by pouring hydrochloric acid into an aqueous solution of silver nitrate.”

Quote B: “This salt has no taste since it is insoluble.”

Quote C: “This compound is completely insoluble in alcohol and even in acids, except in concentrated hydrochloric acid which dissolves it readily.”

Quote D: “On the other hand, silver chloride is highly soluble in aqueous solution of ammonia.”

Quote E: “Then, we can make silver chloride appear again by adding an acid which reacts with ammonia.”

Quote F: “If you take a bowl made of silver to evaporate salty seawater, you will get impure sodium chloride, mixed with a milk-white solid.”

1. **Quote A:** Write the balanced chemical equation of $\text{AgCl}(\text{s})$ synthesis.

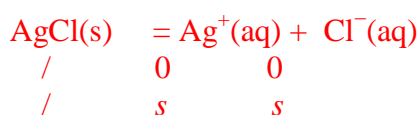
$\text{Ag}^+(\text{aq}) + \text{Cl}^-(\text{aq}) = \text{AgCl}(\text{s})$ (1 point)
Any balanced equation involving also $\text{NO}_3^-(\text{aq})$ or $\text{H}_3\text{O}^+(\text{aq})$ or $\text{H}^+(\text{aq})$ will also be accepted.

0 point if the equation isn't balanced.

Total: 1 point

2. **Quote B:** Calculate the solubility s of $\text{AgCl}(\text{s})$ in water at 298 K in mol L^{-1} .

Calculation:



$$\text{So } [\text{Ag}^+] = [\text{Cl}^-] = s \quad (1 \text{ point})$$

$$K_{s1} = s^2 \quad (1 \text{ point})$$

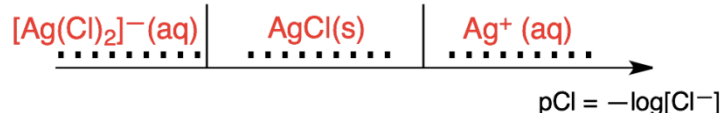
$$\text{so } s = \sqrt{K_{s1}} = \sqrt{10^{-pK_{s1}}} = \sqrt{10^{-9.7}}$$

$$s = 1.41 \cdot 10^{-5} \text{ mol L}^{-1} \quad (1 \text{ point})$$

$$s = 1.0 \cdot 10^{-5} \text{ mol L}^{-1} \text{ will be accepted}$$

Total: 3 points

3. **Quote C:** In a highly concentrated solution of chloride ions, a well-defined complex of stoichiometry 1:2 is formed. On the following qualitative axis (with pCl increasing from left to right), **place** in each domain the silver-containing species that is predominant (or exists, for solids). pCl values at frontiers are not expected.



1 point for each domain correctly attributed

0 point if the same domain is given more than once

Total: 3 points

Quote D: When ammonia is added to silver chloride, a well-defined complex of stoichiometry n is formed.

4. **Write** the balanced equation corresponding to the synthesis of the complex $[\text{Ag}(\text{NH}_3)_n]^+$ from silver chloride and **calculate** the corresponding equilibrium constant.

Equation:



Calculation:



$$K = K_{s1} \beta_n \quad (1 \text{ point})$$

$$K = 10^{-9.7+7.2} = 10^{-2.5} \quad (1 \text{ point})$$

$$= 3.16 \cdot 10^{-3}$$

Total: 3 points

If you could not calculate K , the following value can be used in the rest of the problem: $K = 10^{-3}$

5. Ammonia is added to 0.1 mol of silver chloride in 1 L of water until the last grain of solid disappears. At this moment, $[\text{NH}_3] = 1.78 \text{ mol L}^{-1}$. **Determine** the stoichiometry of the complex neglecting dilution effects.

Calculation:



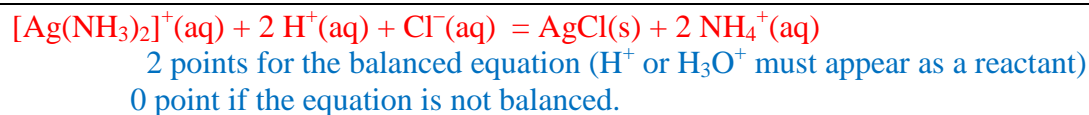
$$K^\circ = \frac{[\text{Ag}(\text{NH}_3)_n^+][\text{Cl}^-]}{[\text{NH}_3]^n} \quad (1 \text{ point})$$

$$\text{so } n = \frac{\log\left(\frac{[\text{Ag}(\text{NH}_3)_n]^+[\text{Cl}^-]}{K^\circ}\right)}{\log([\text{NH}_3])} \quad (1 \text{ point})$$

$$n = 2 \quad (\text{If } K = 10^{-3} \text{ is used, } n = 4 \text{ is found.}) \quad (1 \text{ point})$$

Total: 4 points

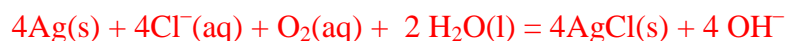
6. **Write** the balanced chemical equation corresponding to **quote E**.



Total: 2 points

7. Assuming that seawater is slightly basic and rich in dioxygen, and that silver metal can reduce dioxygen in such conditions, **write** a balanced chemical equation corresponding to the formation of the solid mentioned in **quote F**. A stoichiometric coefficient of 1 will be chosen for dioxygen. **Calculate** its equilibrium constant at 298 K.

Equation:



(3 points: if correct equation)
without 1 for the stoichiometry for O_2 : -1 point
without AgCl precipitation: -1 point

Calculation:

First possibility:

$$K = 10^{\frac{4}{0.06}[E'(\text{O}_2/\text{HO}^-) - E^\circ(\text{AgCl}/\text{Ag})]} \quad (1 \text{ point})$$

At the equilibrium, all potentials are equal, so:

$$E_{\text{eq}}(\text{AgCl}/\text{Ag}) = E_{\text{eq}}(\text{Ag}^+/\text{Ag}) \quad (1 \text{ point})$$

$$E^\circ(\text{AgCl}/\text{Ag}) + 0.06 \log(1/[\text{Cl}^-]) = E^\circ(\text{Ag}^+/\text{Ag}) + 0.06 \log [\text{Ag}^+]$$

$$\text{so: } E^\circ(\text{AgCl}/\text{Ag}) = E^\circ(\text{Ag}^+/\text{Ag}) + 0.06 \log K_{\text{S1}} = 0.22 \text{ V} \quad (1 \text{ point})$$

$$K = 10^{\frac{4}{0.06}[0.75 - 0.22]} = 2.93 \times 10^{35} \quad (1 \text{ point})$$

$$\text{If } \frac{RT \ln 10}{F} = 0.059 \text{ is used then } K = 10^{\frac{4}{0.059}[0.75 - 0.22]} = 2.57 \times 10^{35}$$

OR

$$\text{Second possibility: } K = (1/K_{\text{S1}})^4 \times 10^{\frac{4}{0.06}[0.75 - 0.80]} \quad (3 \text{ points})$$

$$K = 2.93 \times 10^{35} \quad (1 \text{ point})$$

$$\text{If } \frac{RT \ln 10}{F} = 0.059 \text{ is used then } K = 2.57 \times 10^{35}$$

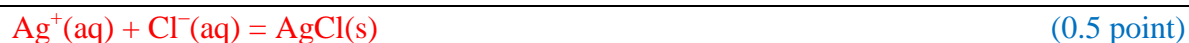
without AgCl precipitation: 1 point for the determination of the constant

Total: 7 points

Part B: The Mohr method

The Mohr method is based on the colorimetric titration of Cl^- by Ag^+ in the presence of potassium chromate (2K^+ , CrO_4^{2-}). Three drops (~ 0.5 mL) of a K_2CrO_4 solution at about $7.76 \cdot 10^{-3} \text{ mol L}^{-1}$ are added to $V_0 = 20.00$ mL of a sodium chloride solution of unknown concentration C_{Cl} . This solution is then titrated by silver nitrate (Ag^+ , NO_3^-) at $C_{\text{Ag}} = 0.050 \text{ mol L}^{-1}$, which immediately leads to the formation of solid **A**. A red precipitate (solid **B**) appears at $V_{\text{Ag}} = 4.30$ mL.

8. **Write** the balanced equations of the two reactions occurring during the experiment. **Calculate** the corresponding equilibrium constants.



$$K^\circ_1 = \frac{1}{K_{\text{S1}}} = 10^{9.7} \quad (0.5 \text{ point})$$



$$K^\circ_2 = \frac{1}{K_{\text{S2}}} = 10^{12} \quad (0.5 \text{ point})$$

Total: 2 points

9. **Identify** the solids.

Solid **A**: $\text{AgCl}(\text{s})$ (1 point)

Solid **B**: $\text{Ag}_2\text{CrO}_4(\text{s})$ (1 point)

Total: 2 points

10. **Calculate** the unknown concentration C_{Cl} of chloride ions in the sodium chloride solution.

Calculations:

At $V_{\text{Ag}} = 4.3$ mL, $n_{\text{Ag}^+, \text{added}} = n_{\text{Cl}^-, \text{introduced}}$ (1 point)

so $C_{\text{Cl}} \times 20 = 0.05 \times V_{\text{Ag}}$ (1 point)

$$C_{\text{Cl}} = 0.011 \text{ mol L}^{-1} \quad (1 \text{ point})$$

Total: 3 points

If you could not calculate C_{Cl} , the value $C_{\text{Cl}} = 0.010 \text{ mol L}^{-1}$ can be used in the rest of the problem.

11. **Calculate** the minimal volume $V_{\text{Ag}}(\text{min})$ for which $\text{AgCl}(\text{s})$ precipitates.

Calculation:

$\text{AgCl}(\text{s})$ precipitates as soon as: $K_{\text{S1}} = Q_{\text{r,eq}} = [\text{Ag}^+][\text{Cl}^-]$ (1 point)

And $[\text{Cl}^-] = C_{\text{Cl}} \times \frac{20}{20.5 + V_{\text{Ag}}(\text{min})} \approx C_{\text{Cl}}$ (1 point)

$[\text{Ag}^+] = \frac{K_{\text{S1}}}{[\text{Cl}^-]} = \frac{0.05 \times V_{\text{Ag}}(\text{min})}{20.5 + V_{\text{Ag}}(\text{min})} \approx \frac{0.05 \times V_{\text{Ag}}(\text{min})}{20.5}$ so $V_{\text{Ag}}(\text{min}) = \frac{20.5 \times K_{\text{S1}}}{0.05 \times [\text{Cl}^-]}$ (1 point)

$$V_{\text{Ag}}(\text{min}) = 8.2 \cdot 10^{-6} \text{ mL with } C_{\text{Cl}} = 0.010 \text{ mol L}^{-1}$$

$$(V_{\text{Ag}}(\text{min}) = 8.4 \cdot 10^{-6} \text{ mL if no approximation } [\text{Cl}^-] \approx C_{\text{Cl}})$$

$$V_{\text{Ag}}(\text{min}) = 7.4 \cdot 10^{-6} \text{ mL with } C_{\text{Cl}} = 0.011 \text{ mol L}^{-1}$$

$$(V_{\text{Ag}}(\text{min}) = 7.6 \cdot 10^{-6} \text{ mL if no approximation } [\text{Cl}^-] \approx C_{\text{Cl}})$$

(1 point)

Total: 4 points

12. **Calculate** the residual concentration $[\text{Cl}^-]_{\text{res}}$ of chloride ions when silver chromate begins to precipitate. **Justify** why CrO_4^{2-} is a good titration endpoint indicator by comparing two values.

Calculation:

$$\text{Ag}_2\text{CrO}_4(\text{s}) \text{ precipitates as soon as: } K_{\text{s}2} = Q_{\text{r,eq}} = [\text{Ag}^+]^2[\text{CrO}_4^{2-}] \quad (1 \text{ point})$$

$$\text{At this moment: } [\text{CrO}_4^{2-}] = \frac{7.76 \times 10^{-3} \times 0.5}{20.5 + V_{\text{Ag}}} = 1.56 \cdot 10^{-4} \text{ mol L}^{-1} \quad (1 \text{ point})$$

$$\text{So: } [\text{Ag}^+] = \sqrt{\frac{K_{\text{s}2}}{[\text{CrO}_4^{2-}]}} = 8.00 \cdot 10^{-5} \text{ mol L}^{-1} \quad (1 \text{ point})$$

$$\text{So: } [\text{Cl}^-]_{\text{residual}} = \frac{K_{\text{s}1}}{[\text{Ag}^+]} \quad (1 \text{ point})$$

$$[\text{Cl}^-]_{\text{res}} = 2.49 \cdot 10^{-6} \text{ mol L}^{-1} \quad (1 \text{ point})$$

CrO_4^{2-} is a good titration endpoint indicator because:

$$[\text{Cl}^-]_{\text{residual}} \ll C \quad (1 \text{ point})$$

Total: 6 points

Problem	Question	1	2	3	4	5	6	7	8	Total
T4 7%	Points	6	9	8	5	6	2	2	12	50
	Score									

Problem T4: From gunpowder to the discovery of iodine

In the 19th century, the French entrepreneur B. Courtois specialized in the production of nitrate **A** ($M_A(NO_3)_m$), used for gunpowder. Initially imported from Asia, **A** was later produced from nitrate **B** ($M_B(NO_3)_n$) using exchange reaction with compound **C**, obtained from algae.

- Find** the formulas of nitrates **A** and **B** knowing that they are anhydrous salts of alkaline or alkaline-earth metal (M_A and M_B). One of the nitrates contains no more than 1 w% of non-metallic impurities while the other contains 9 ± 3 w% of impurities. The content of metals M_A and M_B in the samples is 38.4 w% and 22.4 w% respectively. **Support** your answer with calculations.

We do not know which nitrate **A** or **B** correspond to each amount of impurities, thus we have to check both options. Let's try to apply the condition that there is less than 1% of impurity for both nitrates and check if we find a correct metal in one of both cases. 1% is such a low quantity that it can be neglected.

$$w(M_X) = \frac{M(M_X)}{M(M_X NO_3)} \cdot 100\% \Rightarrow M(M_X NO_3) = \frac{M(M_X)}{w(M_X)} \cdot 100\% = \frac{M(NO_3^-)}{100 - w(M_X)} \cdot 100\%$$

(2 points)

Thus, the mass fraction of M_A in **A** is 38.4% and M_B in **B** is 22.4%:

In **A**:

$$M(M_A) = M(M_A(NO_3)_m) - m \cdot M(NO_3^-) = \frac{62m}{1 - 0.384} - 62m = 38.65m \text{ g mol}^{-1}$$

In **B**:

$$M(M_B) = M(M_B(NO_3)_n) - n \cdot M(NO_3^-) = \frac{62n}{1 - 0.224} - 62n = 17.9n \text{ g mol}^{-1}$$

(2 points)

For the second nitrate we cannot find the correct metal while for the **A**, the metal (M_A) is potassium ($n = 1$).

Thus, for nitrate **B** we have 6 to 12% of impurities, which means that we have 88 to 94% of nitrate. We need to recheck the range of atomic mass of M_B as we have two possible candidates Na and Ca.

The mass fraction of M_B in **B** is between $0.224/0.94 = 0.238$ and $0.224/0.88 = 0.255$.

Thus the molar mass of M_B in **B** is between

$$M(M_B) = M(M_B(NO_3)_n) - n \cdot M(NO_3^-) = \frac{62n}{1 - 0.238} - 62n = 19.36n \text{ g mol}^{-1}$$

And

$$M(M_B) = M(M_B(NO_3)_n) - n \cdot M(NO_3^-) = \frac{62n}{1-0.255} - 62n = 21.22n \text{ g mol}^{-1}$$

Finally we find **B**: $\text{Ca}(\text{NO}_3)_2$ (2 points)

M_A: K and **M_B**: Ca

A: KNO_3 and **B**: $\text{Ca}(\text{NO}_3)_2$

Total: 6 points (3 points for each correct compound).

To obtain **A**, 262.2 g of solid compound **C** were added to the solution containing 442.8 g of **B**. **B** is known to be in excess. As a result, 190.0 g of white precipitate **D** were formed and removed by filtration. The filtrate was evaporated, and the obtained solid mixture **E** was heated until the mass of the sample (containing only nitrites, NO_2^-) was constant. The only gaseous product was dioxygen: 60.48 L at 0 °C at 1 atm (dioxygen can be considered as an ideal gas).

2. **Calculate** the composition (in w%) of mixture **E** considering that it contained only compounds **A** and **B** and no other impurities, and that **C** was taken in pure anhydrous state.

We have the following reaction: $\text{Ca}(\text{NO}_3)_2 + \text{C} \rightarrow \text{KNO}_3 + \text{D(s)}$

As $\text{Ca}(\text{NO}_3)_2$ is in excess thus **C** is the limiting reactant. All compound **C** was consumed and **D** was precipitated, thus the mixture **E** represents a mixture of $\text{Ca}(\text{NO}_3)_2$ in excess and KNO_3 which was formed. Using the mass conservation law, we can calculate the mass of the mix **E**:

$$m(\text{nitrates}) = m(\text{A}) + m(\text{B}) - m(\text{D}) = 442.8 + 262.2 - 190 = 515.0 \text{ g} \quad (2 \text{ points})$$

The reactions of the decomposition of both nitrates can be written:



(1 point for each equilibrated reaction,
-0.5 point per reaction if the coefficients are wrong)

Now we can calculate the amount of O_2 :

$$PV = n(\text{O}_2) \cdot RT$$

$$\Rightarrow n(\text{O}_2) = \frac{PV}{RT} = \frac{101.325 \times 60.48}{8.314 \times 273.15} = 2.70 \text{ mol}$$

(2 points)

[It is not necessary to calculate the amount of O_2 , which is the same as the initial amount of $\text{Ca}(\text{NO}_3)_2$.]

Now we can write the following equation for the numbers of moles, assuming that the mass of **A** is x g and the mass of **B** is $(515 - x)$ g.

$$\frac{x}{2 \times 101} + \frac{515 - x}{164} = 2.70 \Rightarrow x = 383.8 \text{ g} \quad (2 \text{ points})$$

So the mass of **A** (KNO_3) is 383.8 g and the mass of **B** is 131.2 g ($\text{Ca}(\text{NO}_3)_2$).

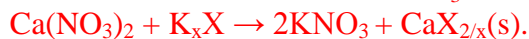
And thus the w% of **A** is 74.5% and w% of **B** is 25.5%. (1 point)

w% of **A**: 74.5 and of **B**: 25.5

Total: 9 points

3. **Determine** the formulas of compounds **C** and **D** and **write** the balanced reaction equation between **B** and **C**.

We can write the reaction of KNO_3 formation as:



Our aim is to find the anion X^{x-} by calculating its molar mass.

If $n(\text{KNO}_3) = 383.8/101 = 3.8 \text{ mol}$, the amount $n(\text{CaX}_{2/x}) = 1.9 \text{ mol}$.

(2 points)

And knowing its mass which is 190 g, we obtain the molar mass of $\text{CaX}_{2/x}$:

$$M(\text{CaX}) = \frac{m}{n} = \frac{190}{1.9} = 100 \text{ g mol}^{-1}$$

The molar mass of Ca is 40 g mol^{-1} , thus the molar mass of $\text{X}^{x-} \times x/2$ is 60 g mol^{-1} and it corresponds to CO_3^{2-} (first we consider that X is a pure element and then we consider that it is binary and contains oxygen).

(2 points)

C: K_2CO_3 and **D:** CaCO_3

(2 points)

Reaction between **B** and **C**:



(2 points)

Total: 8 points

In 1811, when working with algae ashes, Courtois observed that copper vessels were worn out faster than usual. While he was studying this phenomenon, his cat entered the laboratory and spilled the solution of concentrated sulfuric acid on the dry algae ashes: violet vapors instantly came out of the vessel (1, sulfuric acid is the oxidizing agent): iodine (I_2) had just been discovered! Iodine was the cause of the copper corrosion (2). However, because of the medicinal applications of iodine, Courtois opened a new manufacture to produce it by reaction of algae with chlorine (3).

Nowadays, iodine is prepared from the set of reactants (NO_3^- , I^- , H^+) (4) or (IO_3^- , I^- , H^+) (5).

4. **Write** balanced equations for reactions 1–5.

1 $2\text{HI} + \text{H}_2\text{SO}_4 \rightarrow \text{I}_2 + \text{SO}_2 + 2\text{H}_2\text{O}$ (any chemically reasonable redox equation involving I_2 will be accepted) (1 point)

2 $2\text{Cu} + \text{I}_2 \rightarrow 2\text{CuI}$ (1 point)

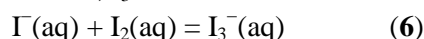
3 $2\text{I}^- + \text{Cl}_2 \rightarrow 2\text{Cl}^- + \text{I}_2$ (1 point)

4 $2\text{NO}_3^- + 6\text{I}^- + 8\text{H}^+ \rightarrow 3\text{I}_2 + 2\text{NO} + 4\text{H}_2\text{O}$
or $2\text{NO}_3^- + 2\text{I}^- + 4\text{H}^+ \rightarrow \text{I}_2 + 2\text{NO}_2 + 2\text{H}_2\text{O}$ (1 point)

5 $\text{IO}_3^- + 5\text{I}^- + 6\text{H}^+ \rightarrow 3\text{I}_2 + 3\text{H}_2\text{O}$ (1 point)

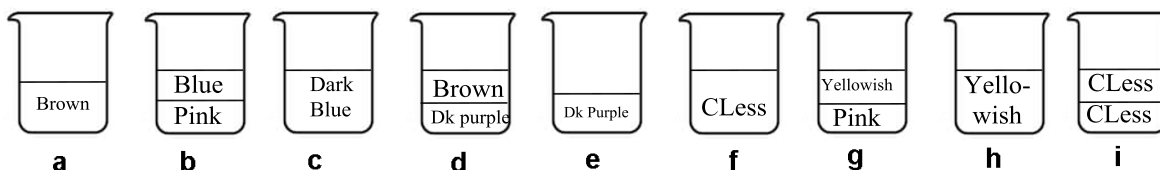
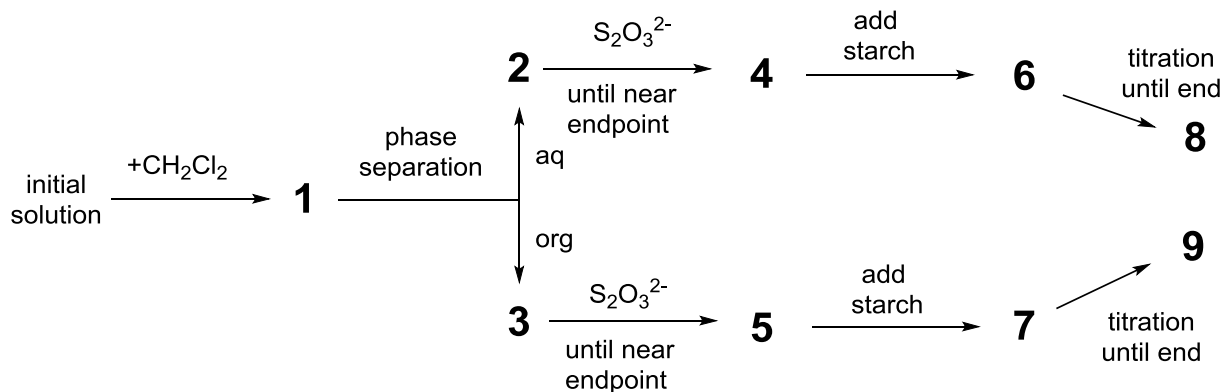
Total: 5 points

The solubility of iodine is very low in water but significantly increases when iodide ions are added. Together they form ions such as triiodide, I_3^- :



Equilibrium (6) can be studied through the extraction of I_2 with dichloromethane. Indeed, I^- and I_3^- do not dissolve in organic solvents but I_2 does and, when extracted, it is 15 times more concentrated in dichloromethane than in water.

The following experiment was performed. To prepare the initial solution, a few crystals of solid iodine were dissolved in 50.0 mL of an aqueous solution of potassium iodide (0.1112 g). Then, 50.0 mL of dichloromethane were added, and the mixture was vigorously shaken until equilibration. After phase separation, each phase was titrated by 16.20 mL (organic phase) and by 8.00 mL (aqueous phase) of the standard aqueous solution of sodium thiosulphate pentahydrate (14.9080 g in 1.000 L of solution) in the presence of starch. The process is schematically represented below:



CLess = colourless Dk = dark

5. **Find** the correspondence between the stages on the scheme (1–9) and the schematic pictures representing them (a–i).

Stages	Picture
1	d
2	a
3	e
4	h
5	g
6	c
7	b
8	f
9	i

Total: 6 points

(1 point for 1, 4 and 5; 0.5 point for the others)

6. **Write** balanced equations for the two possible chemical reactions in the aqueous phase during the titration involving iodine species and sodium thiosulphate.



Total: 2 points

7. **Calculate** the mass of iodine used to prepare the initial solution.

$$C_M(\text{Na}_2\text{S}_2\text{O}_3) = \frac{n(\text{Na}_2\text{S}_2\text{O}_3)}{V} = \frac{m(\text{Na}_2\text{S}_2\text{O}_3)}{M(\text{Na}_2\text{S}_2\text{O}_3) \cdot V} = \frac{14.908}{248.18 \times 1} = 0.060 \text{ mol L}^{-1}$$

The concentration of $\text{Na}_2\text{S}_2\text{O}_3$ solution is then 0.060 mol L^{-1} . (1 point)

$$m(\text{I}_2) = M(\text{I}_2) \cdot n(\text{I}_2) = M(\text{I}_2) \cdot \left(\frac{V_1 + V_2}{1000} \right) \cdot \frac{C_M(\text{Na}_2\text{S}_2\text{O}_3)}{2} = 254 \cdot \left(\frac{16.2 + 8.0}{1000} \right) \cdot \frac{0.06}{2} = 0.184 \text{ g}$$

(0.5 point)

$$m(\text{I}_2) = \quad \mathbf{0.184 \text{ g}} \quad (0.5 \text{ point})$$

Total: 2 points

8. **Calculate** the equilibrium constant K° for equilibrium of reaction (6).

For the organic phase:

$$n(\text{Na}_2\text{S}_2\text{O}_3) = C_M(\text{Na}_2\text{S}_2\text{O}_3) \cdot V = 0.06 \times 16.20 \cdot 10^{-3} = 9.72 \cdot 10^{-4} \text{ mol} \quad (1 \text{ point})$$

Now we can calculate the amount of iodine in aqueous solution using the extraction constant:

$$K_{ex} = \frac{[\text{I}_2]_{org}}{[\text{I}_2]_{aq}} = \frac{\frac{n(\text{I}_2)_{org}}{V_{org}}}{\frac{n(\text{I}_2)_{aq}}{V_{aq}}} = \frac{n(\text{I}_2)_{org}}{n(\text{I}_2)_{aq}} = 15$$

$$\Rightarrow n(\text{I}_2)_{aq} = \frac{n(\text{I}_2)_{org}}{15} = \frac{0.5 \cdot n(\text{Na}_2\text{S}_2\text{O}_3)_{org}}{15} = \frac{0.5 \times 9.72 \cdot 10^{-4}}{15} = 3.24 \cdot 10^{-5} \text{ mol}$$

(2 points)

For aqueous phase:

$$n(\text{I}_2)_{aq} + n(\text{I}_3^-)_{aq} = \frac{1}{2} n(\text{Na}_2\text{S}_2\text{O}_3)_{aq} \quad (1 \text{ point})$$

$$n(\text{Na}_2\text{S}_2\text{O}_3)_{aq} = C_M(\text{Na}_2\text{S}_2\text{O}_3) \cdot V = 0.06 \cdot 8.00 \cdot 10^{-3} = 4.8 \cdot 10^{-4} \text{ mol} \quad (1 \text{ point})$$

$$n(\text{I}_2)_{aq} + n(\text{I}_3^-)_{aq} = \frac{1}{2} C_M(\text{Na}_2\text{S}_2\text{O}_3)_{aq} \cdot V = \frac{1}{2} \cdot 0.06 \cdot 8.00 \cdot 10^{-3} = 2.4 \cdot 10^{-4} \text{ mol} \quad (1 \text{ point})$$

$$n(\text{I}_3^-)_{aq} = [n(\text{I}_2)_{aq} + n(\text{I}_3^-)_{aq}] - n(\text{I}_2)_{aq} = 2.4 \cdot 10^{-4} - 3.24 \cdot 10^{-5} = 2.08 \cdot 10^{-4} \text{ mol} \quad (1 \text{ point})$$

We can calculate the initial number of moles of KI, this amount is equal to the total number of moles of iodide and triiodide in aqueous solution:

$$n(I^-)_{aq} + n(I_3^-)_{aq} = n(KI) = \frac{m}{M} = \frac{0.1112g}{166g/mol} = 6.7 \cdot 10^{-4} mol$$

(1 point)

$$n(I^-)_{aq} = n(KI) - n(I_3^-)_{aq} = 6.7 \cdot 10^{-4} - 2.08 \cdot 10^{-4} = 4.62 \cdot 10^{-4} mol$$

(2 points)

The equilibrium constant is:

$$K_{eq} = \frac{[I_3^-]}{[I^-] \cdot [I_2]} = \frac{2.08 \cdot 10^{-4} / 0.05}{4.62 \cdot 10^{-4} / 0.05 \cdot 3.24 \cdot 10^{-5} / 0.05} = 695$$

$K^\circ = 695$
(2 points)

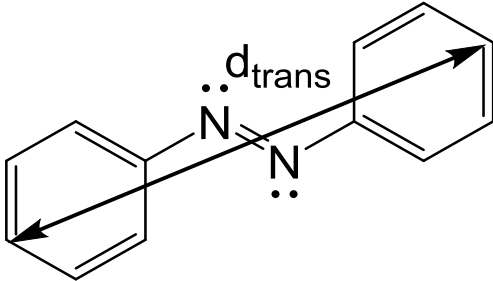
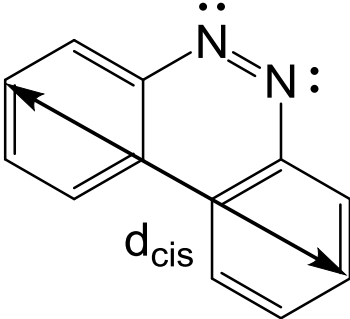
Total: 12 points

Problem T5 8%	Question	1	2	3	4	5	6	7	8	9	10	11	12	Total
	Points	3	4	4	2	5	5	4	3	5	2	2	2	41
Score														

Problem T5: Azobenzene – β -cyclodextrin complexes for the formation of nanomachines

Nanomachines are molecular assemblies that enable the transformation of an energy source into a nano-movement for applications such as drug delivery. Numerous nanomachines make use of the isomerization of azo compounds ($R-N=N-R'$) upon irradiation.

1. **Draw** the stereoisomers of azobenzene ($H_5C_6-N=N-C_6H_5$) and **draw** a line between the two carbon atoms that are the furthest apart. **Compare** these two distances (d_{trans} and d_{cis}).

 <p>(0.5 point: correct <i>trans</i> formula) (Ph, C₆H₅ also accepted, 150° > CNN angles > 100°, correct NCC angles)</p> <p>(0.5 point: correct <i>trans</i> distance scheme) (Ph should be developed to show all C atoms, the arrows should represent exactly the distance between the two extreme C4 and C4' carbon atoms. No approximation.)</p> <p><i>trans</i></p>	 <p>(0.5: point correct <i>cis</i> formula) (Ph, C₆H₅ also accepted, 150° > CNN angles > 100°, correct NCC angles)</p> <p>(0.5 point: correct <i>cis</i> distance scheme) (Ph should be developed to show all C atoms, the arrows should represent exactly the distance between the two extreme carbons (C3-C3' or C4-C4' depending on the drawing, not C3-C4'). No approximation.)</p> <p><i>cis</i></p>
Comparison: $d_{trans} > d_{cis}$ (1 point)	
Total: 3 points	

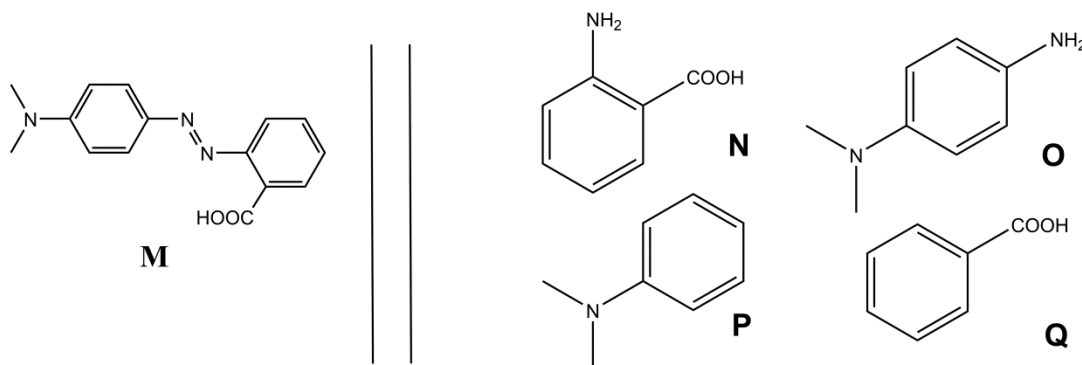


Fig. 1 – Possible reactants for the synthesis of **M**.

2. **M** can be synthesized in two steps from simple reactants (Fig. 1). **Choose** among the suggested reactants (**N** to **Q**) the ones that can provide **M** with very high regioselectivity. Sodium nitrite (NaNO_2) in cold aqueous hydrochloric acid is used as reagent for the first step of the synthesis.

Reactants: **N** and **P**
Total: 4 points (1 point for **O** + **Q**)

Determination of the association constant K_t

β -cyclodextrin (**C**, Fig. 2) is a cyclic heptamer of glucose, which can form inclusion complexes with azo compounds. In tasks 3 to 6, we will determine by spectroscopy the association constant K_t , corresponding to the formation of the inclusion complex CM_{trans} as depicted in Fig. 2.

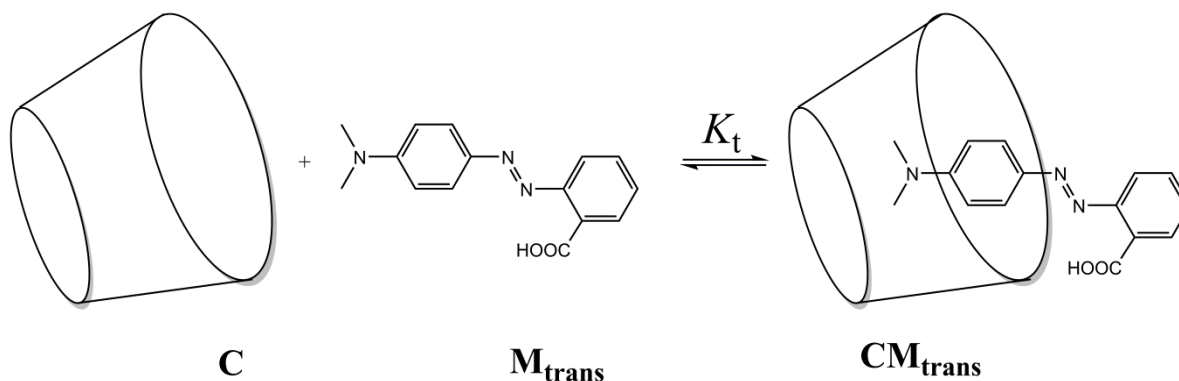


Fig. 2 – Formation of the CM_{trans} inclusion complex.

Several solutions are prepared by mixing **C** and M_{trans} in different proportions to reach initial concentrations $[\text{C}]_0$ and $[\text{M}_{\text{trans}}]_0$. While $[\text{M}_{\text{trans}}]_0$ is identical for all solutions, $[\text{C}]_0$ varies. We follow, at a fixed wavelength, the evolution of the difference in absorbance ΔA between the absorbance of each solution and the pure M_{trans} solution. We note the molar absorption coefficients of CM_{trans} and M_{trans} , $\varepsilon_{\text{CM}_{\text{trans}}}$ and $\varepsilon_{\text{M}_{\text{trans}}}$, respectively. L is the path length of the beam through the sample. The absorbance of **C** (ε_{C}) is negligible.

3. **Demonstrate** that $\Delta A = \alpha \cdot [\text{CM}_{\text{trans}}]$ and **express** α in terms of known constant(s).

Demonstration:

$\Delta A = A(\mathbf{CM}_{\text{trans}}) + A(\mathbf{M}_{\text{trans}}) - A(\text{pure } \mathbf{M}_{\text{trans}} \text{ solutions}):$ (1 point: definition ΔA)

$\Delta A = \varepsilon_{\mathbf{CM}_{\text{trans}}}.L.[\mathbf{CM}_{\text{trans}}] + \varepsilon_{\mathbf{M}_{\text{trans}}}.L.[\mathbf{M}_{\text{trans}}] - \varepsilon_{\mathbf{M}_{\text{trans}}}.L.[\mathbf{M}_{\text{trans}}]_0$ (1 point: Beer Lambert)

As $[\mathbf{M}_{\text{trans}}]_0 = [\mathbf{CM}_{\text{trans}}] + [\mathbf{M}_{\text{trans}}]$ (1 point : mass balance)

$\Delta A = \varepsilon_{\mathbf{CM}_{\text{trans}}}.L.[\mathbf{CM}_{\text{trans}}] + \varepsilon_{\mathbf{M}_{\text{trans}}}.L.([\mathbf{M}_{\text{trans}}]_0 - [\mathbf{CM}_{\text{trans}}]) - \varepsilon_{\mathbf{M}_{\text{trans}}}.L.[\mathbf{M}_{\text{trans}}]_0$
 $= (\varepsilon_{\mathbf{CM}_{\text{trans}}} - \varepsilon_{\mathbf{M}_{\text{trans}}}).L.[\mathbf{CM}_{\text{trans}}]$

$\alpha = L (\varepsilon_{\mathbf{CM}_{\text{trans}}} - \varepsilon_{\mathbf{M}_{\text{trans}}})$ (1 point)

Total: 4 points

4. **Demonstrate** that, when **C** is in large excess with respect to $\mathbf{M}_{\text{trans}}$ (i.e. $[\mathbf{C}]_0 \gg [\mathbf{M}_{\text{trans}}]_0$), the concentration of **C** may be considered as constant, $[\mathbf{C}] \simeq [\mathbf{C}]_0$.

Demonstrations:

$[\mathbf{C}] = [\mathbf{C}]_0 - [\mathbf{CM}_{\text{trans}}]$ (1 point)

$[\mathbf{CM}_{\text{trans}}] < [\mathbf{M}_{\text{trans}}]_0, \ll [\mathbf{C}]_0$, so $[\mathbf{C}] \simeq [\mathbf{C}]_0$ (1 point)

Total: 2 points

5. **Demonstrate** that, when **C** is in large excess with respect to $\mathbf{M}_{\text{trans}}$ (i.e. $[\mathbf{C}]_0 \gg [\mathbf{M}_{\text{trans}}]_0$), $\Delta A = \alpha \cdot \frac{\beta \cdot [\mathbf{C}]_0}{1 + K_t \cdot [\mathbf{C}]_0}$ and **express** β in terms of constant(s) and initial concentration(s).

Demonstration:

$K_t = \frac{[\mathbf{CM}_{\text{trans}}]}{[\mathbf{M}_{\text{trans}}].[\mathbf{C}]}$ (Or $K_t = \frac{[\mathbf{CM}_{\text{trans}}].c^\circ}{[\mathbf{M}_{\text{trans}}].[\mathbf{C}]}$) (1.5 point: K_t)

$[\mathbf{M}_{\text{trans}}]_0 = [\mathbf{CM}_{\text{trans}}] + [\mathbf{M}_{\text{trans}}]$ (0.5 point: mass balance)

So $[\mathbf{M}_{\text{trans}}]_0 = [\mathbf{CM}_{\text{trans}}](1 + \frac{1}{K_t \cdot [\mathbf{C}]})$

So $[\mathbf{CM}_{\text{trans}}] = [\mathbf{M}_{\text{trans}}]_0 \frac{K_t \cdot [\mathbf{C}]}{1 + K_t \cdot [\mathbf{C}]}$

As $[\mathbf{C}] \simeq [\mathbf{C}]_0$, $[\mathbf{CM}_{\text{trans}}] = [\mathbf{M}_{\text{trans}}]_0 \frac{K_t \cdot [\mathbf{C}]_0}{1 + K_t \cdot [\mathbf{C}]_0}$

$\Delta A = \alpha [\mathbf{M}_{\text{trans}}]_0 \frac{K_t \cdot [\mathbf{C}]_0}{1 + K_t \cdot [\mathbf{C}]_0}$

$\beta = K_t [\mathbf{M}_{\text{trans}}]_0$ (3 points)

Total: 5 points

6. **Determine** K_t using the following experimental curve (Fig. 3).

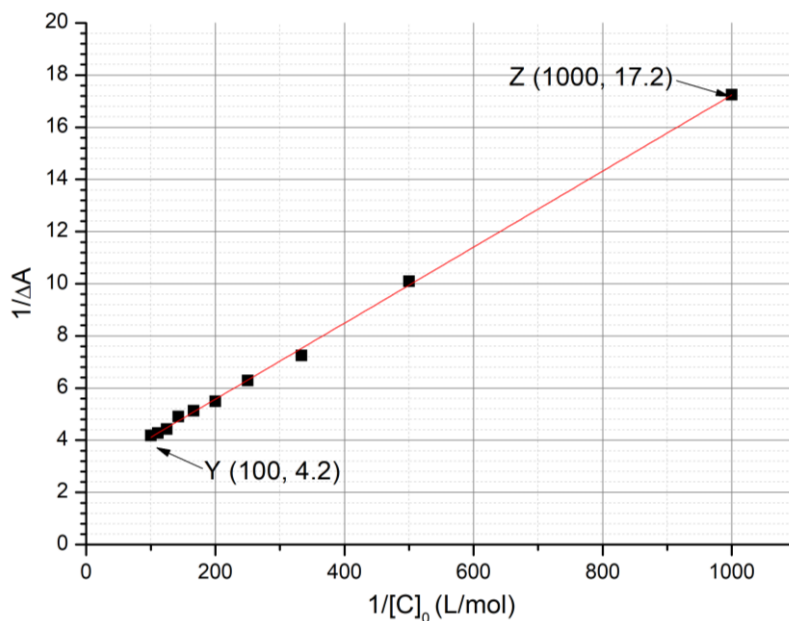


Fig. 3 – Evolution of $1/\Delta A$ as a function of $1/[C]_0$.

Calculations:

$$\frac{1}{\Delta A} = \frac{1}{a\beta} \left(\frac{1}{[C]_0} + K_t \right) \quad (1 \text{ point})$$

$$K_t = \frac{\text{intercept}}{\text{slope}} \quad (1 \text{ point})$$

Using either the graph or linear regression on calculator, we determine the equation

$$\frac{1}{\Delta A} = 0.0144 \left(\frac{1}{[C]_0} \right) + 2.76 \quad (1 \text{ point: } 0.5 \text{ slope} + 0.5 \text{ intercept, within } 10\%)$$

(within $\pm 10\%$ for slope and intercept, no unit needed).

$$\text{Slope} = \frac{yZ - yY}{xZ - xY}; \text{ intercept} = \frac{xZ \cdot yY - xY \cdot yZ}{xZ - xY};$$

$$\text{So } \frac{\text{intercept}}{\text{slope}} = \frac{xZ \cdot yY - xY \cdot yZ}{yZ - yY}$$

$$K_t = \frac{1000 \times 4.2 - 100 \times 17.2}{17.2 - 4.2}$$

$$K_t = 191 \quad (2 \text{ points if within } 10\%, 1 \text{ point if within } 20\%)$$

Total: 5 points

Determination of the association constant K_c

In tasks 7 to 9, we will determine by kinetic studies the association constant K_c , corresponding to the formation of the inclusion complex with M_{cis} , CM_{cis} . A sample containing only M_{trans} is irradiated, thus producing a known amount of M_{cis} , $[M_{cis}]_0$. M_{cis} (free or within the inclusion complex) then thermally isomerizes into M_{trans} . In the absence of C , the isomerization follows a first order kinetics with a rate constant k_1 . All complexation equilibria are faster than the isomerization processes. The kinetic scheme corresponding to this experiment is provided in Fig. 4.

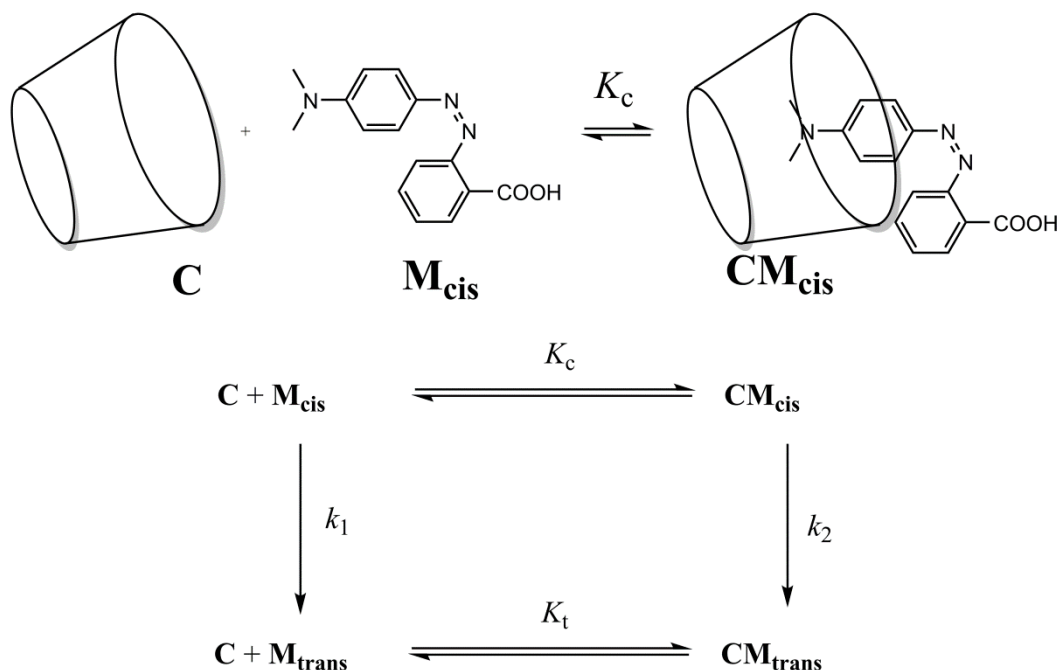


Fig. 4 – Kinetic scheme for the isomerization of M_{cis} in the presence of C .

The rate of disappearance r for the total amount of M_{cis} (free and complexed) is defined as

$$r = k_1[\text{M}_{\text{cis}}] + k_2[\text{CM}_{\text{cis}}]$$

Experimentally, r follows an apparent first order kinetic law with an apparent rate constant k_{obs} :

$$r = k_{\text{obs}}([\text{M}_{\text{cis}}] + [\text{CM}_{\text{cis}}])$$

7. **Demonstrate** that $k_{\text{obs}} = \frac{\gamma + \delta \cdot k_2[\text{C}]}{1 + K_c[\text{C}]}$ and **express** γ and δ in terms of known constant(s).

Demonstration:

$$k_{\text{obs}}([\text{M}_{\text{cis}}] + [\text{CM}_{\text{cis}}]) = k_1[\text{M}_{\text{cis}}] + k_2[\text{CM}_{\text{cis}}] \quad (0.5 \text{ point})$$

$$\text{and } K_c = \frac{[\text{CM}_{\text{cis}}]}{[\text{M}_{\text{cis}}][\text{C}]} \quad (1.5 \text{ point: } K_c)$$

$$\text{so } [\text{CM}_{\text{cis}}] = K_c [\text{C}] [\text{M}_{\text{cis}}]$$

$$\text{So } k_{\text{obs}}([\text{M}_{\text{cis}}] + K_c [\text{C}] [\text{M}_{\text{cis}}]) = k_1[\text{M}_{\text{cis}}] + k_2 K_c [\text{C}] [\text{M}_{\text{cis}}],$$

Which can be written as:

$$k_{\text{obs}} = \frac{k_1 + K_c \cdot k_2[\text{C}]}{1 + K_c[\text{C}]}$$

$$\gamma = k_1 \quad (1 \text{ point})$$

$$\text{and } \delta = K_c \quad (1 \text{ point})$$

Total: 4 points

8. **Choose** in which condition(s) the half-life $t_{1/2}$ corresponding to k_{obs} can be expressed as

$$t_{1/2} = \frac{\ln 2}{\gamma} (1 + K_c[\text{C}]_0) \text{ given that } [\text{C}]_0 \gg [\text{M}_{\text{cis}}]_0. \text{ Mathematically justify your answer.}$$

Very slow isomerization of M_{cis} within cyclodextrin (2 points)

Very slow isomerization of free M_{cis}

CM_{cis} very stable

CM_{trans} very stable

0 for any other answer, or multiple answers.

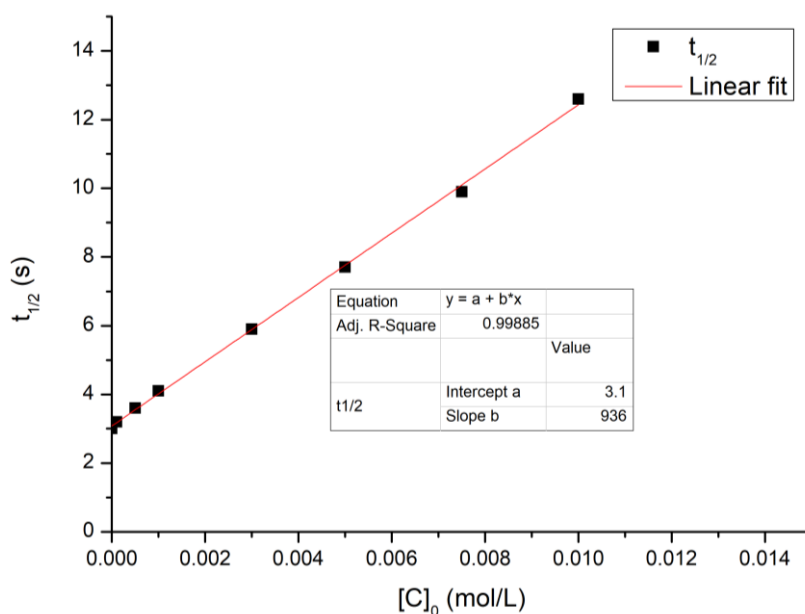
Demonstration:

We need $k_{\text{obs}} \approx \frac{\gamma}{1+K_c[C]}$, so $\gamma \gg k_2 [C]_0$, so $k_2 \approx 0$: slow isomerization (1 point)

Total: 3 points

9. Assuming the condition(s) in task 8 satisfied, **determine** K_c by a linear regression using the data below. You may use a calculator or plot a graph.

$[C]_0$ (mol L ⁻¹)	$t_{1/2}$ (s)	$[C]_0$ (mol L ⁻¹)	$t_{1/2}$ (s)
0	3.0	$3.0 \cdot 10^{-3}$	5.9
$1.0 \cdot 10^{-4}$	3.2	$5.0 \cdot 10^{-3}$	7.7
$5.0 \cdot 10^{-4}$	3.6	$7.5 \cdot 10^{-3}$	9.9
$1.0 \cdot 10^{-3}$	4.1	$1.0 \cdot 10^{-2}$	12.6



Equation of the linear regression:

Using a graphical representation or linear regression on the calculator one can determine:

$$t_{1/2} = \frac{\ln 2}{\gamma} (1 + K_c [C]_0) = 3.1 + 936 [C]_0 \quad (2 \text{ points : 1 slope + 1 intercept within 20\%})$$

$$K_c = \frac{\text{slope}}{\text{intercept}} \quad (1 \text{ point})$$

$$K_c = 302 \quad (2 \text{ points})$$

Total: 5 points**Formation of nanomachines**

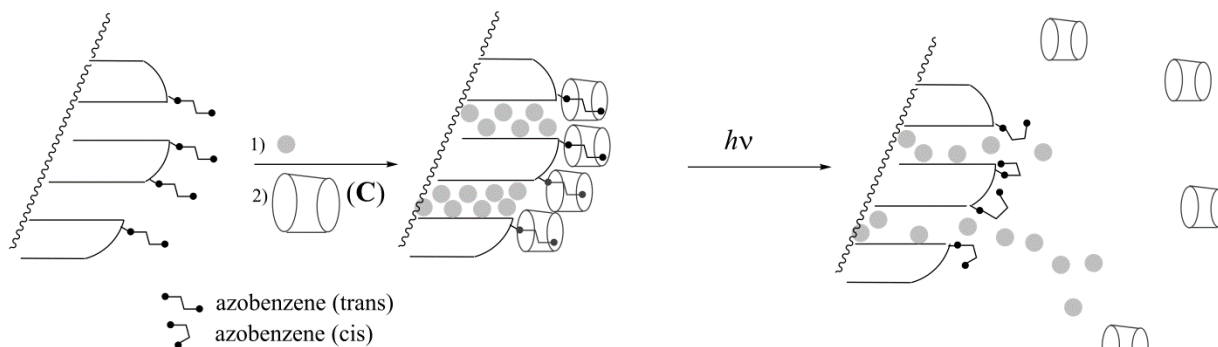


Fig. 5 – Cleavage of an azobenzene–cyclodextrin inclusion complex induced by a light-triggered isomerization, which allows delivery of a dye (grey circles).

Another azobenzene compound (for which $K_c \ll K_t$), initially in the *trans* form, is covalently grafted on silica (Fig. 5). The silica pores are filled with a dye (rhodamine B, grey circles in Fig. 5). Upon addition of **C**, an inclusion complex is formed, which blocks the pores and prevents the release of the dye.

10. **Choose** the most appropriate condition (one choice only) so that the pores are initially blocked in the presence of **C**, and the dye can be released upon irradiation.

- | | |
|---|------------|
| <input type="checkbox"/> $K_t \gg 1$ | (1 point) |
| <input checked="" type="checkbox"/> $K_t \gg 1$ and $K_c \ll 1$ | (2 points) |
| <input type="checkbox"/> $K_t / K_c \ll 1$ | (0 point) |
| <input type="checkbox"/> $K_t \gg 1$ and $K_c \gg 1$ | (0 point) |
| <input type="checkbox"/> $K_c \ll 1$ | (1 point) |

0 point if multiple answers except for $K_c \ll 1$ AND $K_t \gg 1$: 1 point

Total: 2 points

This azobenzene-silica powder loaded with a dye is placed in the corner of a cuvette (Fig. 6) so that the powder cannot move into solution. The powder is irradiated at a wavelength λ_1 to trigger the release of the dye from the pores (Fig. 5). To monitor this release by absorbance spectroscopy we measure the absorbance of the solution at wavelength λ_2 .

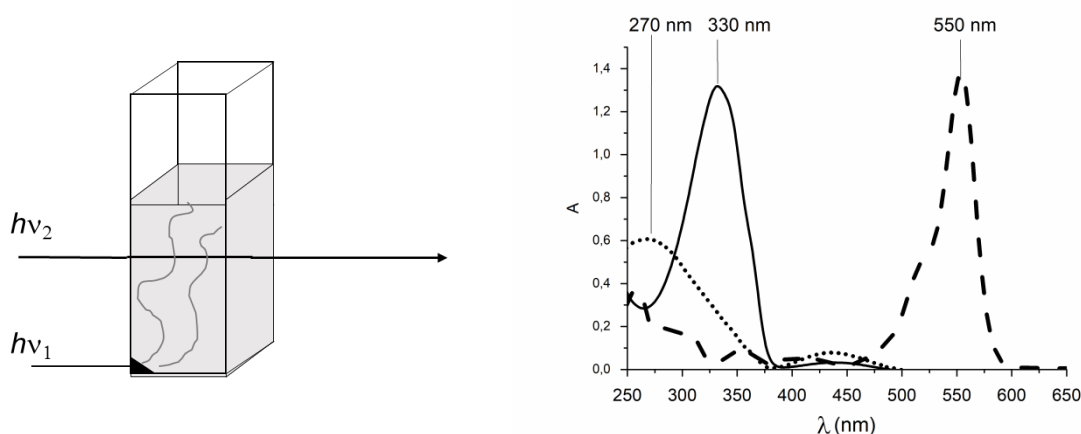


Fig. 6 – Left: experimental setup used to monitor the release of the dye; right: absorption spectra of *trans*-azobenzene (full line), *cis*-azobenzene (dotted line) and rhodamine B (dashed line).

11. **Determine** λ_1 .

$\lambda_1 = 330$ nm (*trans* azobenzene is irradiated to form the *cis* compound which dissociates)

Total: 2 points

12. **Determine** λ_2 .

$\lambda_2 = 550$ nm (the release of the dye into solution is monitored)

Total: 2 points

Problem	Question	1	2	3	4	5	6	7	8	9	Total
T6 8%	Points	4	4	5	3	10	2	9	6	5	48
	Score										

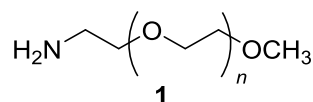
General remarks:

- For an incorrectly carried out calculation, 0.5 points are subtracted.
- Unless stated otherwise, – 0.5 point for minor mistakes, including wrong valency, missing carbon or hydrogen atom on a heteroatom or wrong/missing charge.

Problem T6: Characterization of a block-copolymer

Block-copolymers, obtained by linking different polymers (blocks), have unique properties, such as the ability to self-assemble. In this problem, the synthesis and characterization of such macromolecules are studied.

Study of the first block



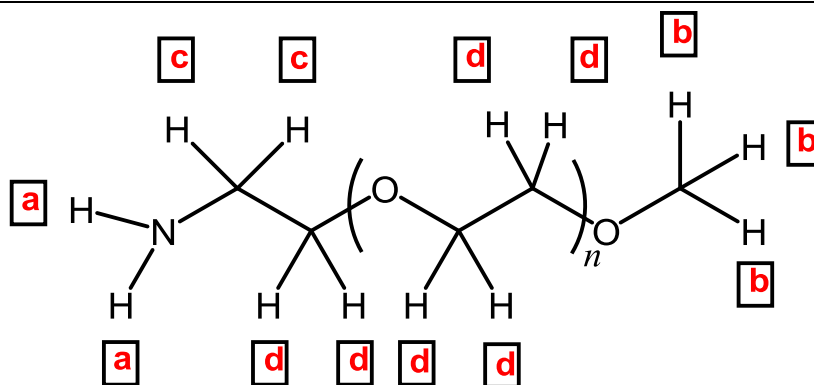
In this first part, we will study the water soluble homopolymer **1** (α -methoxy- ω -aminopolyethyleneglycol).

The ^1H NMR spectrum of **1** (DMSO- d_6 , 60 °C, 500 MHz) includes the following signals:

Index	δ (ppm)	Peak Area
a	2.7*	0.6
b	3.3	0.9
c	3.4	0.6
d	~ 3.5	133.7

Table 1, *in the presence of D_2O , the signal at 2.7 ppm disappears.

- Match** the ^1H NMR signals (a, b, c, d) from Table 1 with each of the corresponding protons.



Total: 4 points

–1 point for each misassigned or unassigned group of equivalent protons, irrespective of the exact number of misassigned/unassigned protons for a group.
0 point for three or more misassigned or unassigned groups

2. **Express** the average degree of polymerization n as a function of the area $A_{\text{OC}_2\text{H}_4}$ of the NMR peak of the repeating unit and the area A_{OCH_3} of the NMR peak of the methyl end group. **Calculate** n .

$$n = (A_{\text{OC}_2\text{H}_4}/4)/(A_{\text{OCH}_3}/3) \quad A_{\text{OC}_2\text{H}_4} = A_d - 0.6$$

(3 points)

1.5 if any proportionality relation

$$n = \frac{133.1 \cdot 3}{0.9 \cdot 4} = 111$$

(1 point)

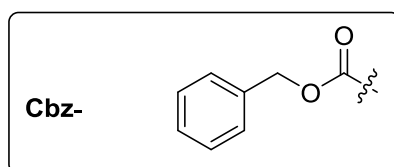
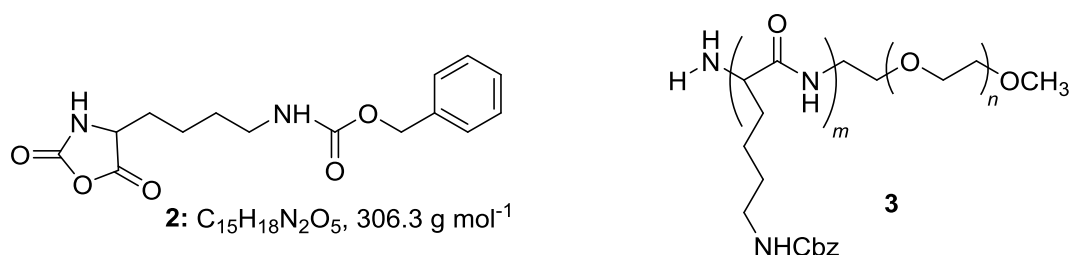
$$n = 111$$

Total: 4 points

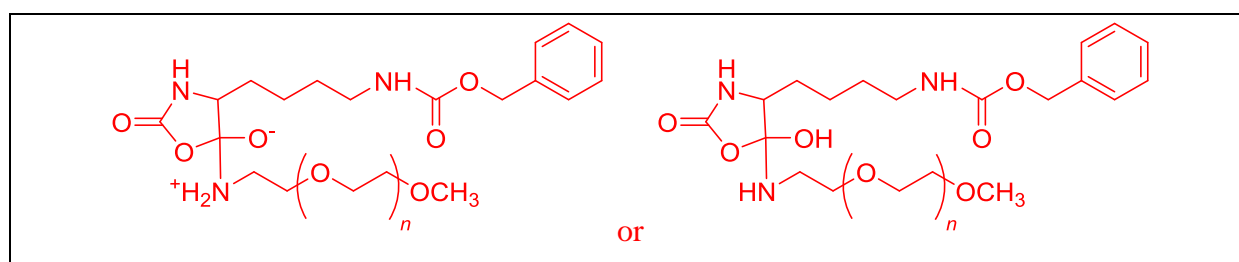
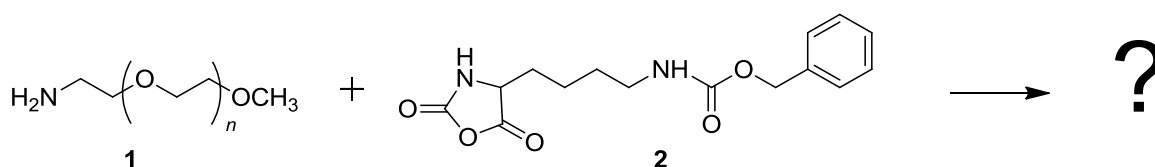
If you could not calculate n , the value $n = 100$ can be used in the rest of the problem.

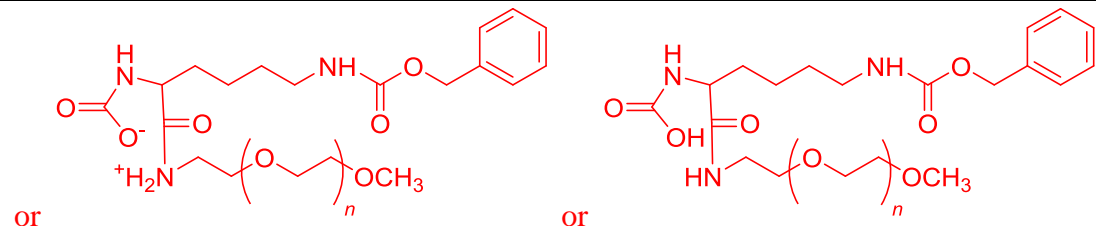
Study of a diblock-copolymer

The synthesis of the second block of the copolymer is performed through the reaction of **1** with **2** (ϵ -(benzyloxycarbonyl)-lysine *N*-carboxyanhydride). This yields the block-copolymer **3**.



3. **Draw** the reaction intermediate that is formed in the first step of the addition of **1** to **2**. The second step of the mechanism leads to the formation of a gas molecule, **G**. **Draw** its structure.





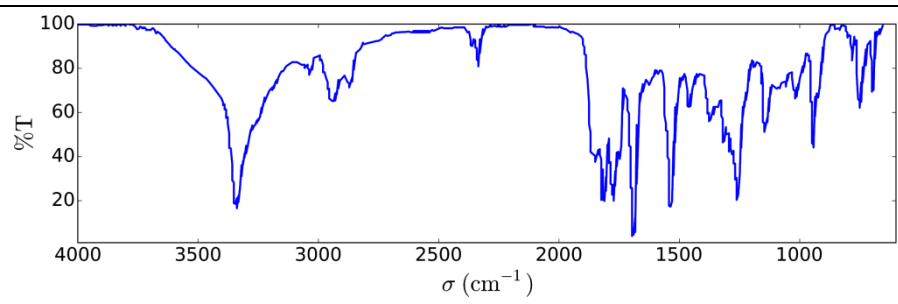
or

(4 points:
2 points for an intermediate resulting from a nucleophilic attack
drawn towards one of the two carbonyl groups at the *N*-carboxy anhydride moiety)
(2 points for choosing the OCOCH carbon, consistent with the final structure)

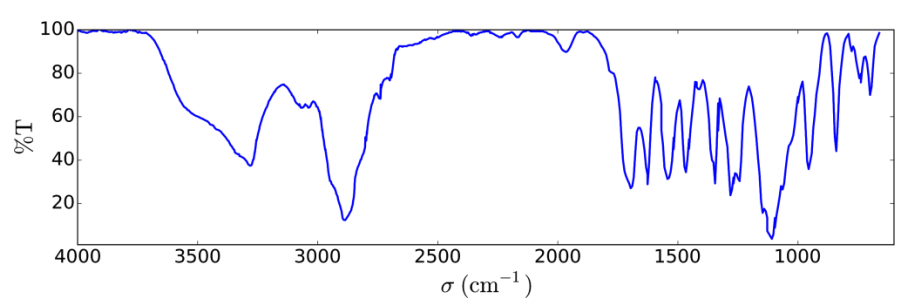
X: CO₂ (1 point)

Total: 5 points

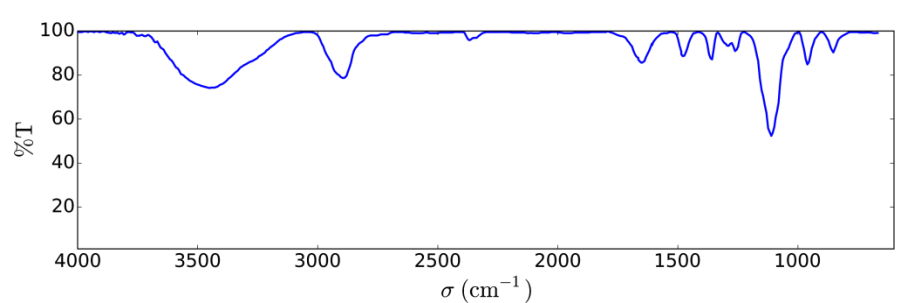
4. Infrared (IR) measurements are performed to characterize the compounds. **Match** the three IR spectra with compounds **1**, **2** and **3**.



Compound: 1 2 3



Compound: 1 2 3



Compound: 1 2 3

(1 point per correct answer)
selecting at least twice the same compound number leads to 0 point for the question

Total: 3 points

5. The ^1H NMR spectrum of copolymer **3** (in $\text{DMSO-}d_6$, at $60\text{ }^\circ\text{C}$, 500 MHz) is reported in Fig. 1. Using some or all of the NMR signals, the areas of which are reported in Table 2, **calculate** its number average molar mass M_n , considering n from question 2. For your calculations, **draw** a circle around the group(s) of atoms you used and **give** their corresponding symbol(s) ($\alpha, \beta \dots$).

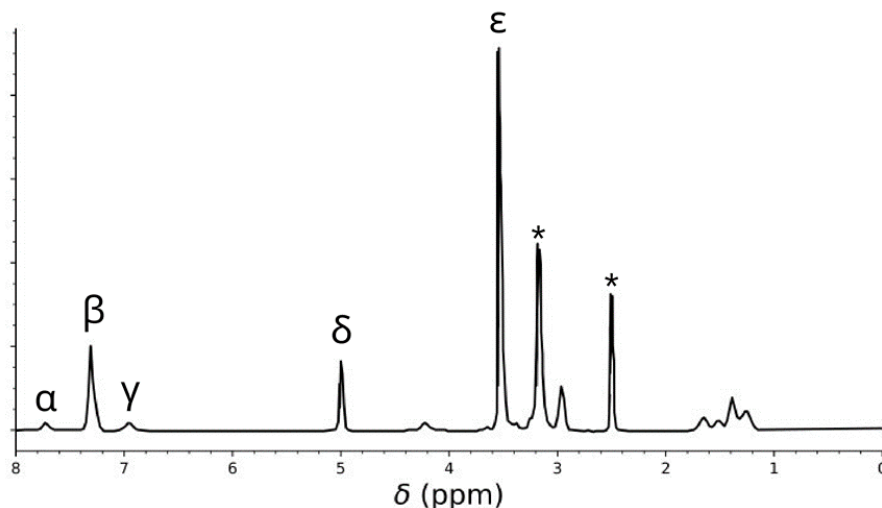
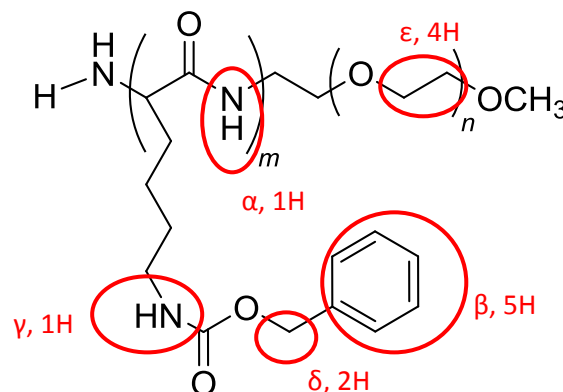


Table 2

Peak	Area
α	22.4
β	119
γ	23.8
δ	47.6
ϵ	622

Fig. 1 – signals marked with * correspond to the solvent and water.



(3 points for the choice and identification of ϵ (1 point) and at least one of the signals α, β, γ or δ (2 points))

N.B.: attributing the carbamate signal to an amide and *vice versa* will also be accepted and given full mark

Calculations for n :

n is the same as in question 2, which allows to calculate the conversion factor χ between the relative number of protons in the molecule and the area of the NMR peak (peak that has the same chemical shift as signal δ in question 1).

$$n = 111, A_\epsilon = 622, \rightarrow \chi = 622/(4 \times 111) = 1.4 \quad (\chi = 1.6 \text{ for } n = 100)$$

(2 points, 0 if the conversion factor (or equivalent) is assumed to be 1 or if conversion factors from question 1 are used)

Calculation of m :

$$\text{For example: } m = A_\beta/5\chi = 17 \text{ (for } n = 111), m = 14.9 \text{ (for } n = 100)$$

(3 points)

Calculation of M_n :

Number average molar mass, using $m = 17$, $n = 111$:
 $M_n = 111 \times 44 + 262 \times 17 + 1 + 31 + 43 = 9.41 \text{ kg mol}^{-1}$

$$M_n = 9.41 \text{ kg mol}^{-1}$$

Provide your answer with two decimal places.

(2 points)

–1 point if the ending groups are not taken into account (then $0.075 \text{ kg mol}^{-1}$ will be missing)

–0.5 point if incomplete ending groups

Total: 10 points

This reaction of **1** with **2** yielded the copolymers **3a** after 20 h, **3b** after 25 h and **3c** after 30 h of reaction at 40°C . Results of size-exclusion chromatography (SEC) experiments are presented in Fig. 2.

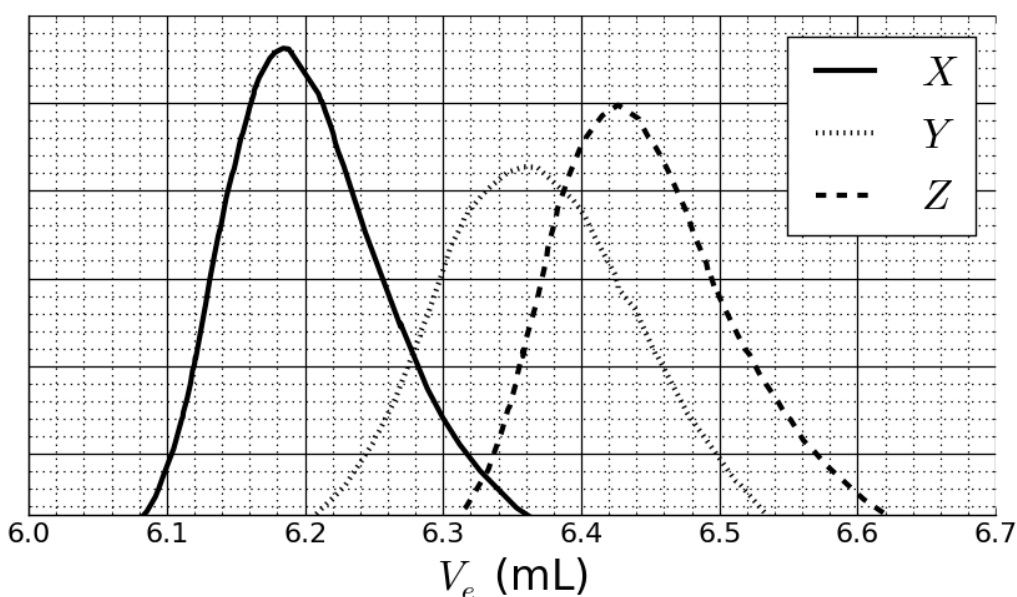


Fig. 2 – SEC chromatograms of **3a**, **3b** and **3c** as a function of the elution volume, V_e .

6. **Match** the signals in Fig. 2 with the copolymers **3a**, **3b** and **3c**.

3a:	<input type="checkbox"/> X	<input type="checkbox"/> Y	<input checked="" type="checkbox"/> Z
3b:	<input type="checkbox"/> X	<input checked="" type="checkbox"/> Y	<input type="checkbox"/> Z
3c:	<input checked="" type="checkbox"/> X	<input type="checkbox"/> Y	<input type="checkbox"/> Z

Total: 2 points if everything is correct.

0 point for any other answer

In order to calibrate the chromatogram, a mixture of standard polymers of known masses (3, 30, 130, 700 and 7000 kg mol^{-1}) has been studied (Fig. 3).

The log value of the molar mass is a linear function of the elution volume, V_e .

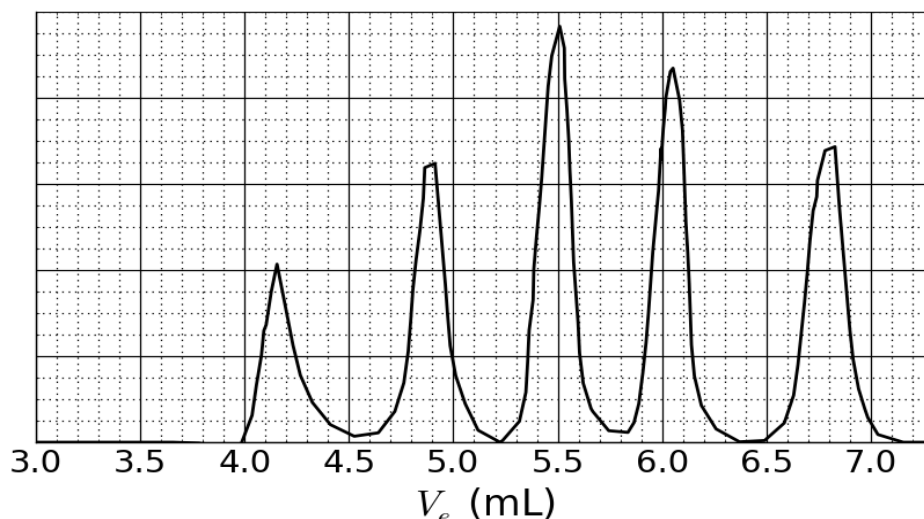


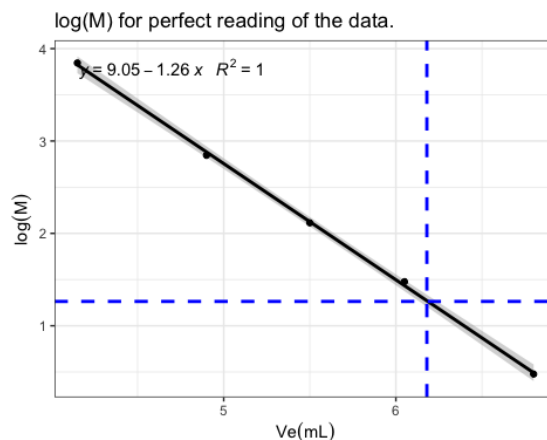
Fig. 3 – SEC chromatogram of the mixture of standards.

7. Based on the SEC curves in Fig. 2 and 3, **determine** V_e of the polymer that corresponds to curve X and use it to **estimate** the degree of polymerization m of its second block. **Detail** your calculation; you may use a calculator or plot a graph.

$V_e =$ mL

The elution volume $V_e(X)$ has a peak at 6.18 mL (1 point for correct reading ± 0.01 mL)

Determination of a function such as $\log M$ or $\ln M = a \times V_e \text{ (mL)} + b$ either graphically or numerically.



$$\log(M) = 9.05 - 1.26 \times V_e \text{ (mL)} \text{ or } \ln(M) = 9.05 - 1.26 \times V_e \text{ (mL)}$$

In case of a mistake in the relation between the standard masses and the elution volumes, such a graph could also be obtained and the answers derived from it will also be taken into account.

(4 points)

–1 point if wrong function but good choice of values

–1 point if a linear function of type $\log(M) = a \cdot V_e$ is used

–1 if the sign of the slope is not consistent with Q6

Calculation of the molar mass, $M_n(X)$:

The use of the calibration allows to determine the value of $M_n(X)$:

$$\log M_n(X) = -1.26 \times 6.18 + 9.05 \quad \text{so } M_n = 18.3 \text{ kg mol}^{-1} \quad (1 \text{ point})$$

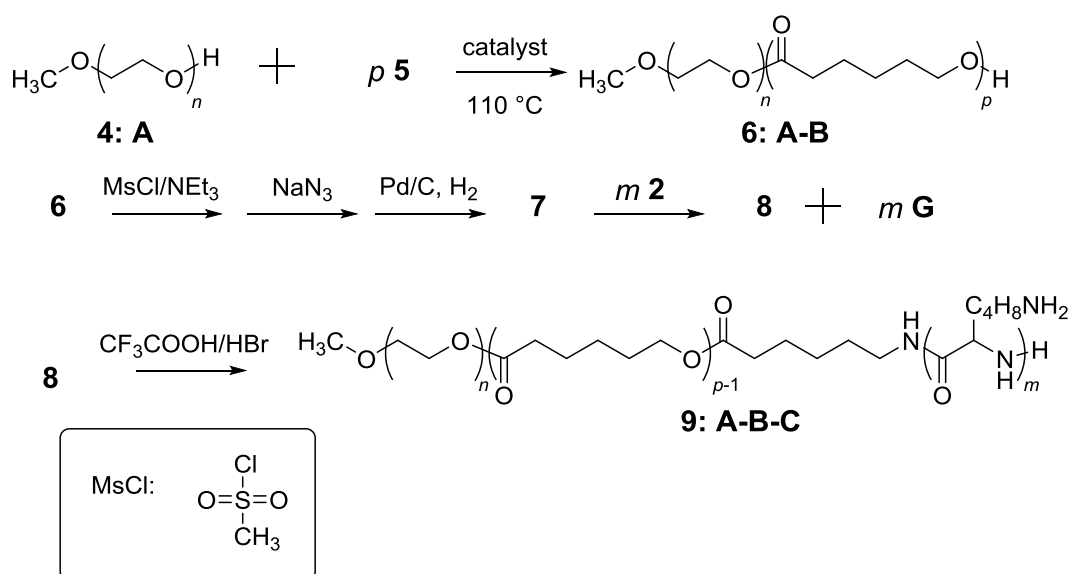
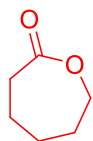
Calculation of m from the molar mass:

$m = (M_n(\mathbf{X}) - M(\mathbf{1}))/262 = (M_n(\mathbf{X}) - 44n - 75)/262$ (75 g mol⁻¹ correspond to the end groups)
 or, for instance:
 $m = [18330 - 100 \times 44 - 75]/262 = 52$ (for $n = 100$)
 $m = [18330 - 111 \times 44 - 75]/262 = 51$ (for $n = 111$)
 $m = 51$

(3 points)

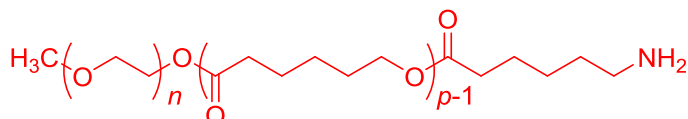
Total: 9 points**Triblock copolymer synthesis**

For biological applications, involving the formation of micelles, a triblock copolymer **9** can be synthesized through the introduction of a middle block, **B**, using monomer **5**.

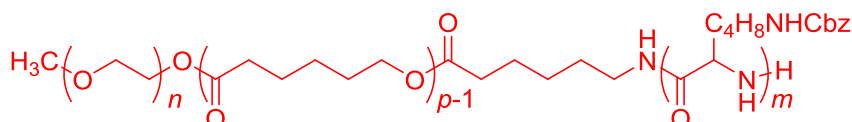
8. **Draw** the structures of **5**, **7** and **8**.**5** (no other products than **6:A-B** are obtained)

(2 points)

linear acid instead of the caprolactone: 0 point

7 (a gas is formed in the final step)

(2 points)

8

(2 points)

Total: 6 points

9. Amphiphilic block copolymers, such as **9: A-B-C**, can be used for medical applications, as they self-assemble into micelles in water (pH = 7), which can be used as drug carriers. **Assign** each block of the copolymer to a property. **Draw** a scheme of the micelle with only 4 polymer chains.

A: hydrophobic hydrophilic

B: hydrophobic hydrophilic

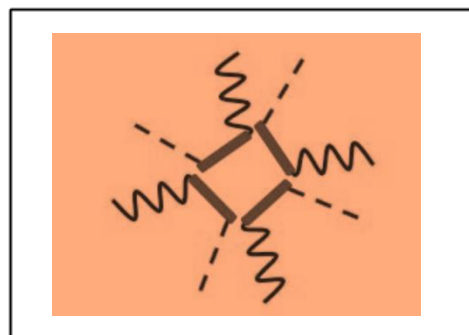
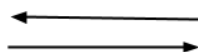
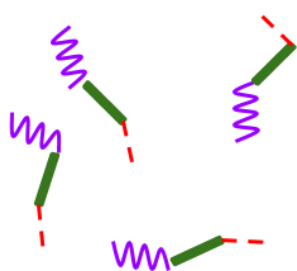
C: hydrophobic hydrophilic

(3 points)

A 

B 

C 



(2 points for correct micelle assembly, in accordance with the predicted property)

Hydrophile/hydrophobe/hydrophile case: 1 point if a sheet-like structure instead of a micelle

Total: 5 points

Problem	Question	1	2	3	4	5	6	7	8	9	10	11	Total
T7 6%	Points	4	12	2	2	2	5	5	8	4	5	5	54
	Score												

Problem T7: Ring motion in a [2]catenane

In 2016, the Nobel Prize in Chemistry was awarded to J.-P. Sauvage, Sir J. F. Stoddart and B. L. Feringa "for the design and synthesis of molecular machines". An example of these is [2]catenane, a molecule consisting of two interlocked rings. In this system, one macrocycle contains a single phenanthroline (bidentate) ligand and the second contains two ligands: a phenanthroline and a terpyridine (tridentate) ligand. A copper ion is coordinated by one ligand from each macrocycle. Depending on the oxidation state of the copper (+I or +II), two configurations are obtained (Fig. 1).

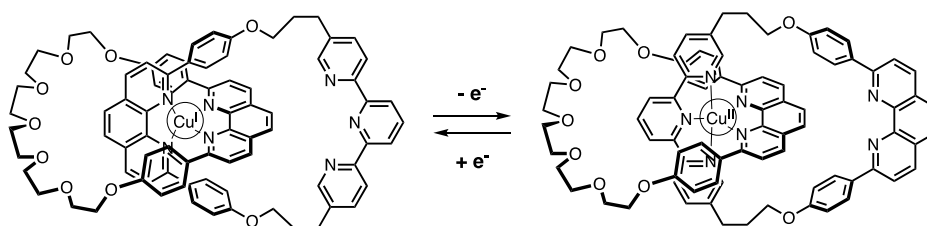
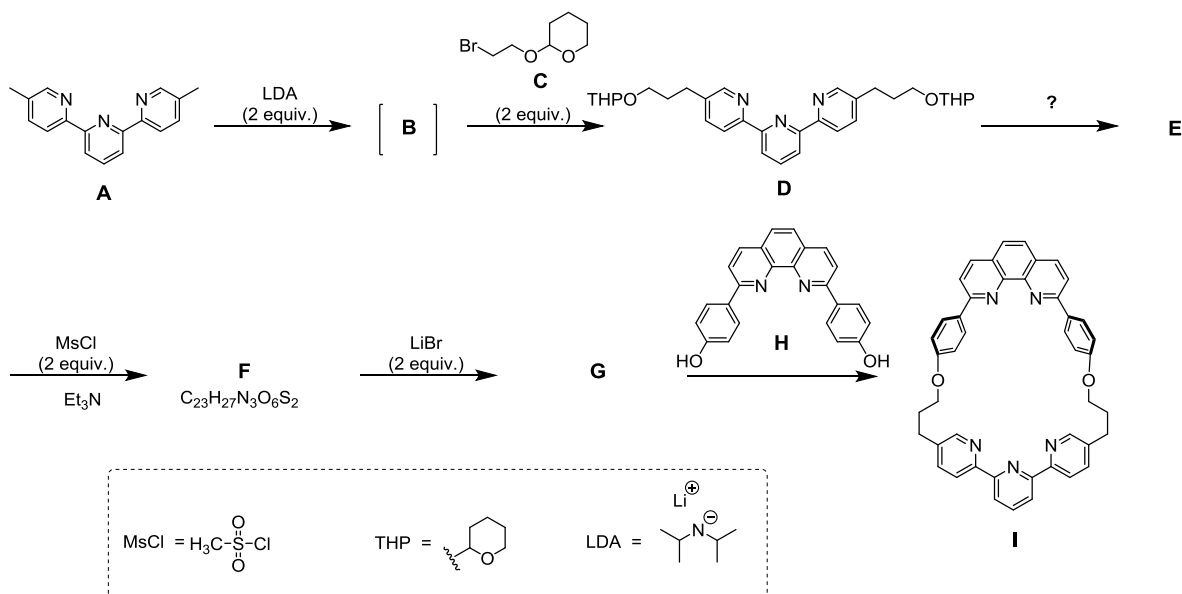
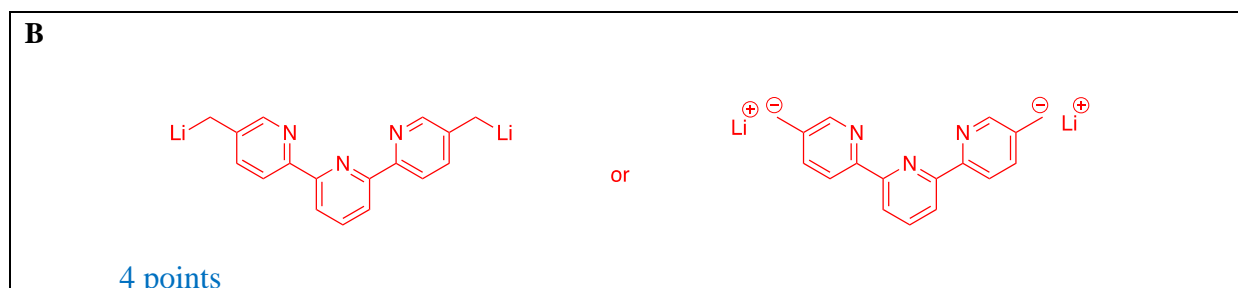


Fig. 1 – Multi-stability of a ring in a [2]catenane.

The synthesis of the macrocycle is the following:



1. **Draw** the structure of **B**.

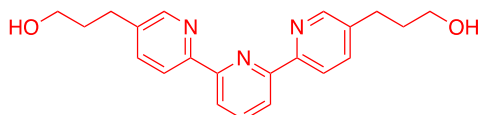


- 2 points for mono deprotonated species
 -1 point if a + charge appears instead of the - charge
 -2 points for minor errors (wrong number of carbon atoms in alkyl chains,...)
 -1 point for missing double bond in pyridine ring

Total: 4 points

2. **Draw** the structures of **E**, **F** and **G**.

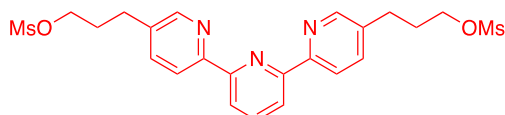
E



4 points

- 2 points for monodeprotected compound
 -2 points for minor errors

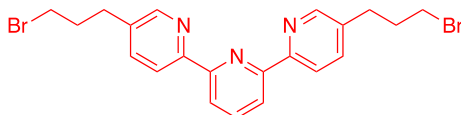
F



4 points

- 0 point if not correct molecular formula
 -2 points for minor errors

G



4 points

- 2 points for monosubstituted compound
 -2 points for minor errors

Total: 12 points

3. Out of the following the reaction conditions, **choose** which one(s) can produce **E** from **D**:

- H^+ , H_2O (2 points)
 OH^- , H_2O
 NaBH_4 , CH_3OH
 H_2 , Pd/C , THF

-1 point for each incorrect answer. The total score in question 3 may not be negative.

Total: 2 points

4. In the synthetic strategy, MsCl is used to obtain:

- a leaving group (2 points)
 a protecting group

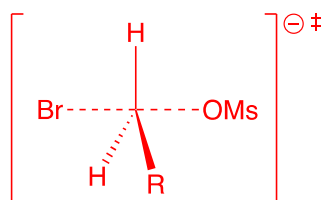
- a deactivating group
 a directing group
 0 point for any other or multiple answers
Total: 2 points

5. **G** is obtained by the reaction between **F** and LiBr in acetone. This reaction is:

- electrophilic aromatic substitution
 nucleophilic aromatic substitution
 S_N1
 S_N2 (2 points)
 0 point for any other or multiple answers
Total: 2 points

6. **Draw** the transition state of the rate-determining step of the reaction **F** → **G**, showing the 3D geometry. Depict only one reaction center. The main carbon chain can be represented as an R group.

Transition state:

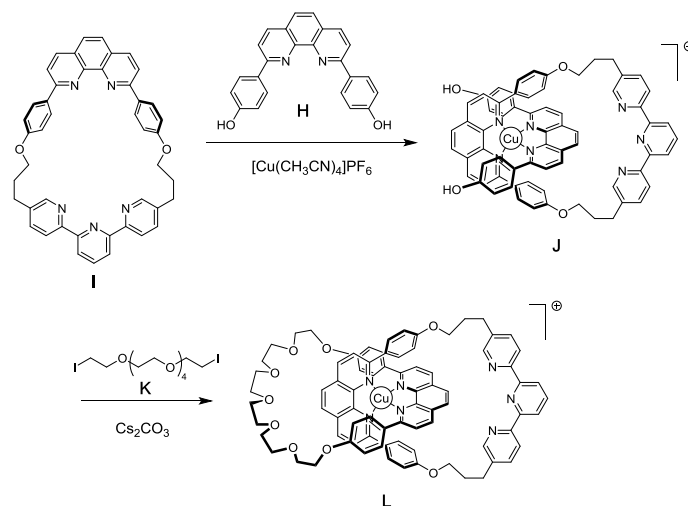


- 0 point if wrong geometry or disposition of the groups
 -1 point for the absence of a global (-1) charge or of two partial (δ^-) charges
 -1 point if no dashed bonds for Br—C and MsO—C
 -2 points if R = RCH₂ (*ie* R includes the stereogenic carbon atom)

The total score in question 6 may not be negative.

Total: 5 points

The synthesis of [2]catenane **L** uses the template effect of a copper complex:



7. **Write** the full electronic configuration of Cu(0) in its ground state. Give the oxidation state of Cu in complex **J** and write the electronic configuration of Cu in the free ion corresponding to **J**.

Electronic configuration of Cu(0):

$[\text{Ar}]4s^13d^{10}$ or $1s^22s^22p^63s^23p^64s^13d^{10}$ (2 points)

1 point for $[\text{Ar}]4s^23d^9$

1 point for $4s^13d^{10}$

1 point if both $[\text{Ar}]4s^23d^9$ and $[\text{Ar}]4s^13d^{10}$ configurations are given.

Oxidation state of Cu in **J**:

+1 or +I

(1 point)

Cu^+ notation also accepted

Electronic configuration of Cu in **J**:

$[\text{Ar}]3d^{10}$ or $1s^22s^22p^63s^23p^63d^{10}$ (2 points)

2 points for other electronic configurations, if in agreement with the oxidation state

1 point for $[\text{Ar}]4s^13d^9$ if $[\text{Ar}]4s^23d^9$ was given as electronic configuration of Cu(0)

1 point for $3d^{10}$ but 2 points if $[\text{Ar}]$ is already missing in the electronic configuration of Cu(0)

Total: 5 points

8. **Select** the geometry of the copper ion in **L**. Assuming an ideal geometry of the ligands around the copper center, **draw** the electronic levels of the d orbitals subject to the crystal field. **Fill** the orbital diagram. **Give** the maximum value of the spin (*S*) for this complex.

The geometry of Cu in **L** is:

Octahedral

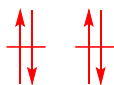
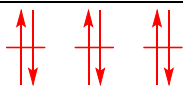
Tetrahedral

Square planar

Trigonal bipyramid

(2 points)

Splitting and filling of d orbitals:



3 points for orbital splitting
1 point for electron filling

(4 points)

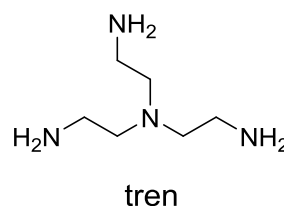
 $S = 0$

(2 points)

Total: 8 points

9. Out of the following compounds, **choose** the one(s) that can remove the copper ion in **L** to obtain the free [2]catenane:

- CH_3CN
 NH_4PF_6
 KCN
 tren



2 points for each correct answer
 -1 point if CH_3CN is selected
 -1 point if NH_4Cl is selected
 The total score in question 10 may not be negative.

Total: 4 points

In [2]catenane **L**, the copper ion can exist in two oxidation states (+I) or (+II), and each of them exhibits a different coordination sphere (tetra- or penta-coordinated, respectively).

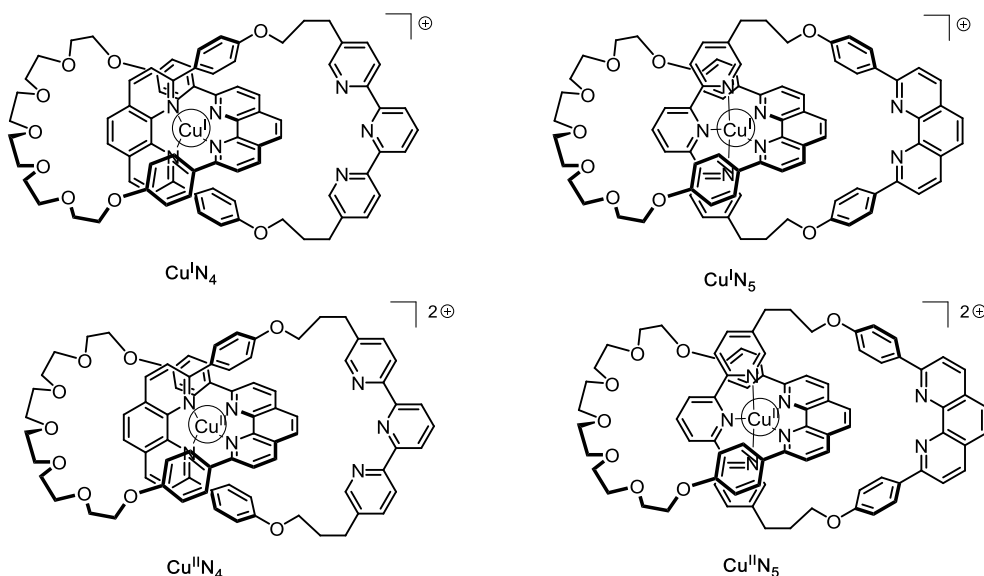


Fig. 2 – [2]catenane **L** states

The stability of Cu(I) complexes can be inferred by comparing their electronic structures to that of a noble gas.

10. **Fill** in the blanks with a number or a tick:

The $\text{Cu}^{\text{I}}\text{N}_4$ complex has **18** electrons in the coordination sphere of the metal.

The $\text{Cu}^{\text{I}}\text{N}_5$ complex has **20** electrons in the coordination sphere of the metal.


The $\text{Cu}^{\text{I}}\text{N}_4$ complex is more / less stable than the $\text{Cu}^{\text{I}}\text{N}_5$ complex.

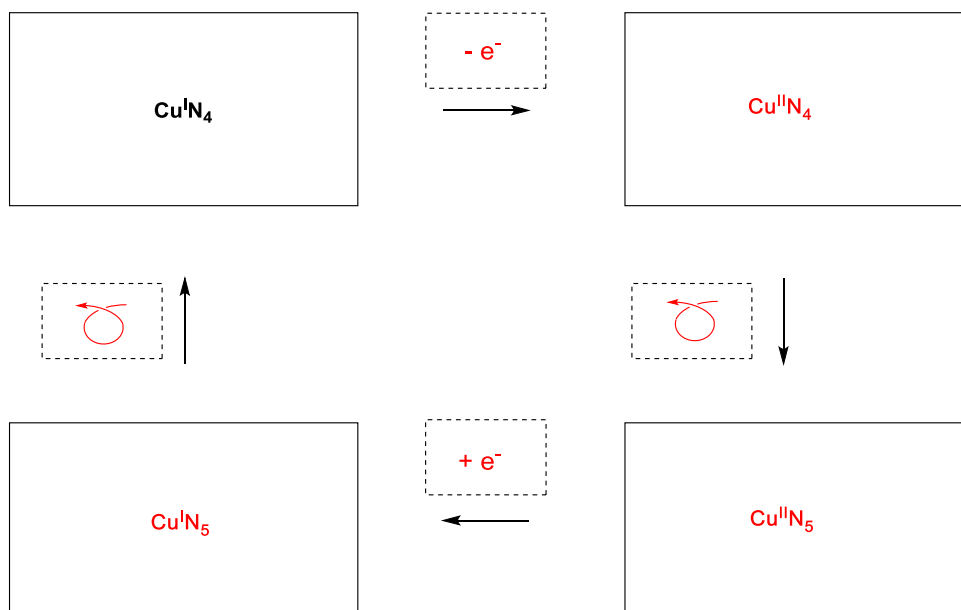
2 points for each correct number of valence electrons

1 point for correct more / less choice

Total: 5 points

11. **Fill** in the solid boxes with the designation of the involved complexes in Fig. 2 and **complete** the sequence to achieve electrochemical control of the system using the following notation for the

dashed boxes:  (rotation) ; + e⁻ ; - e⁻.



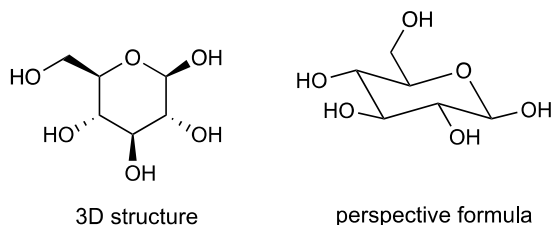
1 point for each correct assignment of complexes
 0.5 point for each correct assignment on the arrows

Total: 5 points

Problem	Question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
T8 6%	Points	2	6	2	2	11	2	4	3	4	2	6	8	2	6	4	64
	Score																

Problem T8: Identification and synthesis of inositols

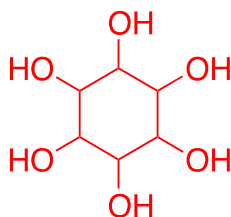
In this problem, we define “3D structure” and “perspective formula” as indicated for β -glucose in the following figure.



Inositols are cyclohexane-1,2,3,4,5,6-hexols. Some of these 6-membered carbocycles, in particular *myo*-inositol, are involved in a number of biological processes.

Structure of *myo*-inositol

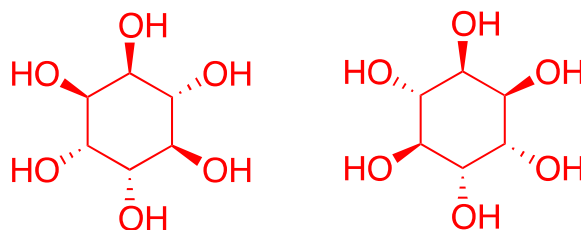
- Draw** the structural formula of inositols, without stereochemical details.



Total: 2 points for the correct structure

This family of molecules contains 9 different stereoisomers, including enantiomers.

- Draw** all 3D structures of the stereoisomers that are optically active.



Total: 6 points if both enantiomers are given

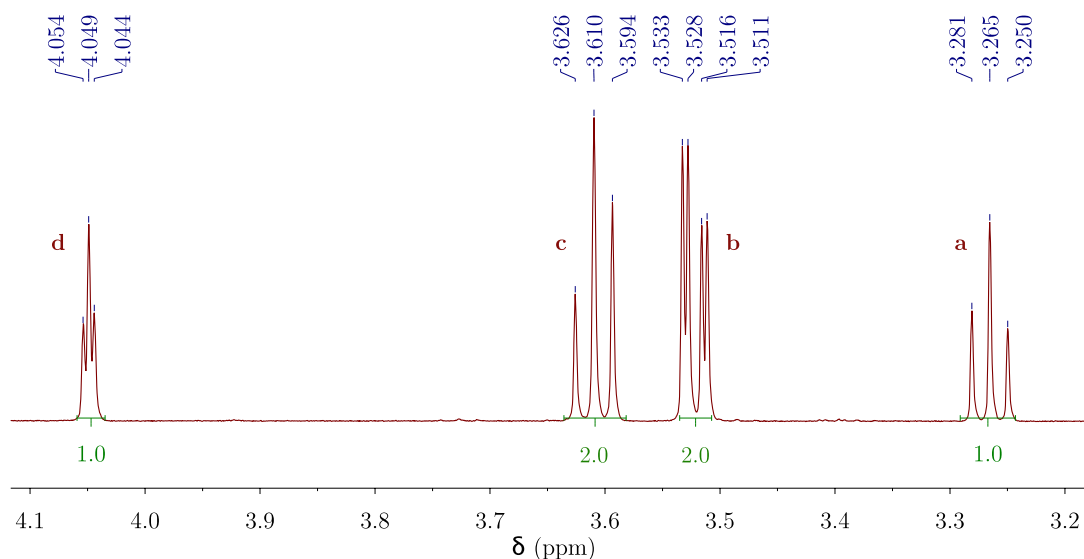
3 points if only one enantiomer with the correct stereochemistry is given

3 points if the two correct perspective formulas are given

-2 points for each other stereoisomer

The total score in question 2 may not be negative

The structure of a specific inositol, called *myo*-inositol, is studied here. Only one of its chair conformers is predominant and its structure can be deduced from its ^1H NMR spectrum. The spectrum below was obtained at 600 MHz in D_2O . No other signal from that compound was observed in the spectrum. The integration is indicated on the spectrum below each signal.



3. **Give** the molecular formula of the predominant compound derived from *myo*-inositol in this sample that is consistent with the number of protons observed in the ^1H NMR spectrum.

$\text{C}_6\text{H}_6\text{O}_6\text{D}_6$

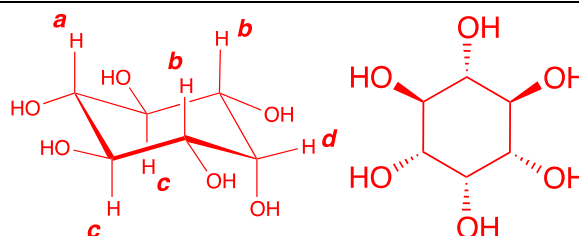
Total: 2 points (1 point if wrong structure containing D)

4. Based on the number and integrations of the proton signals, **give** the number of symmetry plane(s) that exist(s) in this molecule.

1

Total: 2 points

5. **Complete** the following perspective drawing of the most stable conformation of *myo*-inositol. Then **label** each hydrogen with the corresponding letter (**a**, **b**, **c** or **d**) according to the NMR spectrum above. Proton **a** must be on carbon **a** on the following representation. **Draw** its 3D structure.



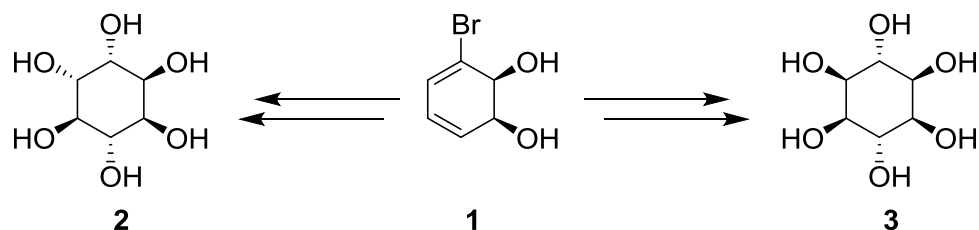
Total: 11 points

- 3 points if the correct perspective drawing of the most stable conformer is given
 1 point if the stereoisomer is correct but it is not the most stable conformer
 1 point if the all-equatorial isomer is depicted

6 points for the correct attribution of the chemical shifts
 3 points if the attribution is correct but with H non depicted
 2 points for the correct 3D structure

Synthesis of inositols

For medicinal applications, it is useful to synthesize some inositol phosphates on a large scale. We will study the synthesis of inositol **2** from bromodiol **1**.



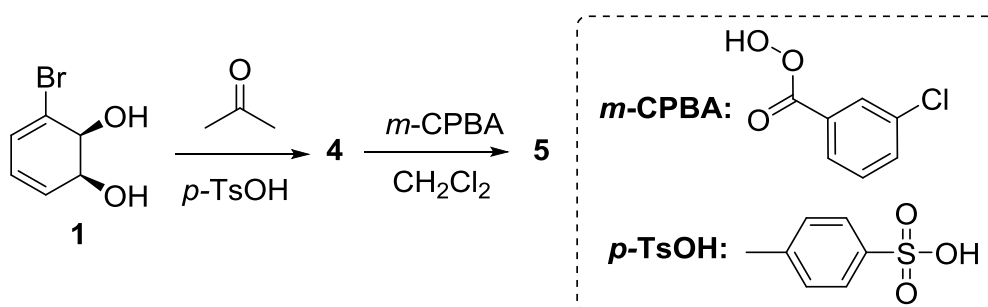
6. **Choose** the correct structural relationship(s) between **2** and **3**.

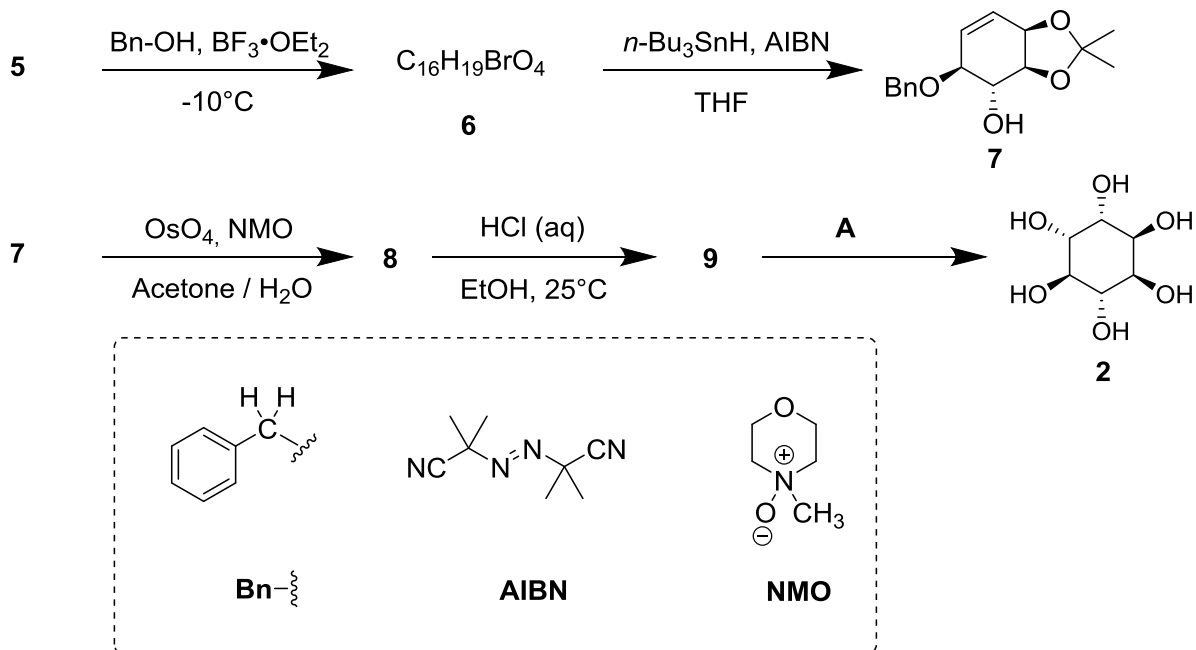
- enantiomers
 epimers
 diastereomers
 atropoisomers

Total: 2 points

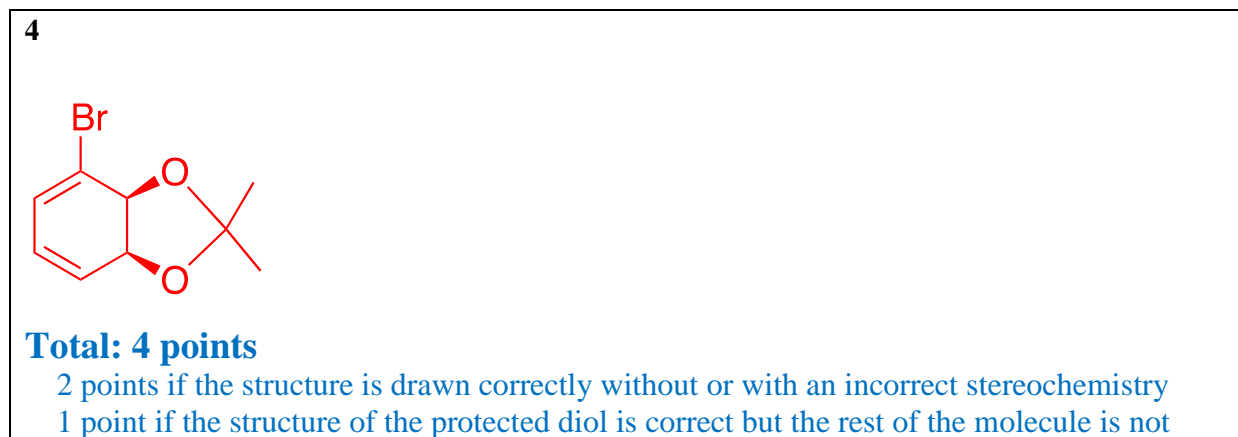
–1 point per incorrect answer given

Inositol **2** can be obtained from compound **1** in 7 steps.

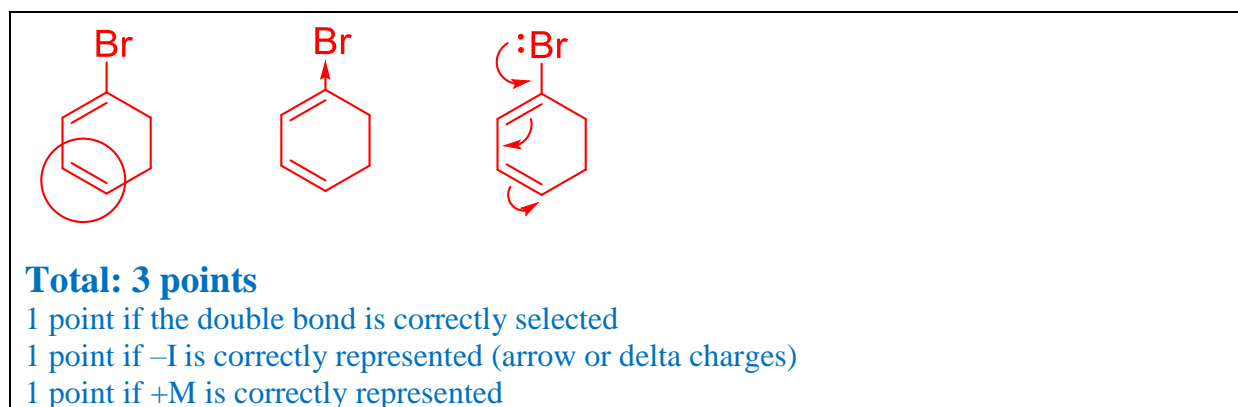




7. **Draw** the 3D structure of **4**.

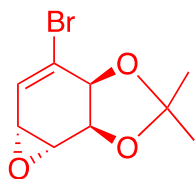


8. The reaction leading to **5** occurs on the double bond with the highest electron density. Consider below the structure of 1-bromo-1,3-cyclohexadiene, which is a substructure of **4**. **Circle** the double bond with the highest electron density. **Represent** all the electronic effects due to the bromine.



9. **Draw** the 3D structure of the major diastereomer **5**.

5



Total: 4 points

- 2 points if the structure is drawn correctly without or with an incorrect stereochemistry
 2 points if a bromonium bridge additional to the epoxide is depicted
 1 point if the structure is drawn with an incorrect regioselectivity but with the correct stereochemistry
 0.5 point if the structure is drawn with an incorrect regioselectivity and an incorrect stereoselectivity

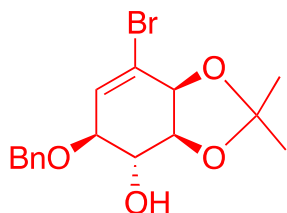
10. **Give** the total number of stereoisomers of **5** possibly obtained by this synthesis, starting from enantiopure compound **1**.

2

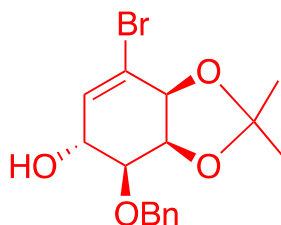
Total: 2 points

11. For the step **5** → **6**, another product with the same molecular formula, denoted **6'**, can be produced. **Draw** the 3D structures of **6** and **6'**.

6



6'

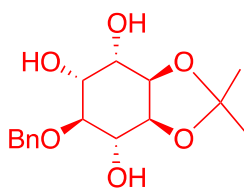


Total: 6 points for both molecules

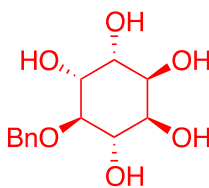
1 point for each structure drawn correctly without or with an incorrect stereochemistry

12. **Draw** the 3D structures of major diastereomers **8** and **9**.

8



9



Total: 8 points for both molecules

2 points for each structure drawn correctly without or with an incorrect stereochemistry
For 9: 2 points if Bn is also deprotected, 0 point if only Bn is deprotected

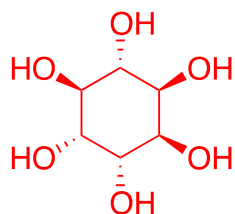
13. **Select** the right set(s) of conditions **A** to obtain **2**.

- H₂, Pd/C
 K₂CO₃, HF
 HCOOH, H₂O
 BF₃·OEt₂

Total: 2 points

–1 point for each incorrect answer given

14. If the bromine is not present in compound **1**, in addition to **2**, another stereoisomer would be obtained. Considering that the stereoselectivity of the reactions that take place in the synthesis remains unchanged and that the following steps involve the same number of equivalents as for **2**, **draw** the 3D structure of this stereoisomer and **give** its relationship with **2**.



4 points

2 points if the structure is drawn correctly with an incorrect stereochemistry for the dihydroxylation

2 points if the structure is drawn correctly with an incorrect stereochemistry for the addition of BnOH

3 points if Bn is still present

- enantiomers
 epimers
 diastereoisomers
 atropoisomers

2 points if the answer is consistent with the previous structure

–1 point for each incorrect answer

Total: 6 points

15. During the synthesis of **2** from **1**, **choose** the removal step(s) of protecting or directing groups.

- 1 → 4
 4 → 5
 5 → 6
 6 → 7
 7 → 8
 8 → 9
 9 → 2

Total: 4 points if all correct steps are given

–1 point if 6 → 7 is missing

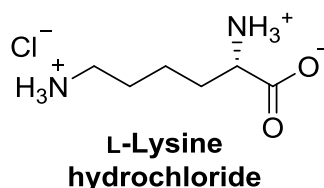
–2 points if 8 → 9 or 9 → 2 is missing or if another step is chosen

Problem	Question	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
T9 7%	Points	2	2	4	3	2	17	1	1	2	4	2	2	2	44
	Score														

Problem T9: Synthesis of levobupivacaine

Part I.

The local anesthetic bupivacaine (marketed as Marcaine) is on the World Health Organization List of Essential Medicines. Although the drug is currently used as a racemic mixture, it was demonstrated that one enantiomer of bupivacaine, levobupivacaine, is less cardiotoxic and, therefore, safer than the racemate. Levobupivacaine can be synthesized from the natural amino acid L-lysine.



Note on grading: unless stated otherwise, -1 point for minor mistakes, including wrong valency, missing hydrogen atom on a heteroatom or wrong/missing charge.

- Assign** the absolute configuration of the stereogenic center in L-lysine hydrochloride and **justify** your answer by classifying the substituents in order of their priority.

Configuration:	Priority 1 > 2 > 3 > 4:
<input type="checkbox"/> R <input checked="" type="checkbox"/> S	
<p>2 points for both correct answers, no partial points.</p> <p>Total: 2 points</p>	

- The prefix L in L-lysine refers to relative configuration. **Choose** all correct statements:

- | |
|--|
| <input type="checkbox"/> All natural L-amino acids are levorotatory.
<input checked="" type="checkbox"/> Natural L-amino acids can be levorotatory or dextrorotatory.
<input type="checkbox"/> All natural L-amino acids are (S).
<input type="checkbox"/> All natural L-amino acids are (R). |
|--|

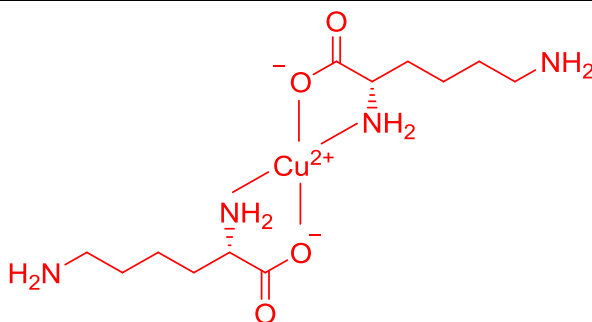
2 points for the correct answer. 0 points if any incorrect answer.

Total: 2 points

Often, we want only one of the amino groups in L-lysine to react. A Cu^{2+} salt with excess aqueous hydroxide can selectively mask the reactivity of one of the amino groups. After the complex is formed, only the non-complexed NH_2 group is available to react.

- Considering that L-lysine acts as a bidentate ligand and that two L-lysines coordinate to one Cu^{2+} ion in the presence of aqueous hydroxide, **draw** the structure of the intermediate complex.

Complex



4 points (both planar (*cis* and *trans*) and tetrahedral structures accepted).

–1 point if one or both $\epsilon\text{-NH}_3^+$ instead of $\epsilon\text{-NH}_2$.

–2 points if one or both $\alpha\text{-NH}_3^+$ instead of $\alpha\text{-NH}_2$.

–2 points if $\epsilon\text{-NH}_2$ group is coordinated together with the carboxylate.

–2 points if COOH instead of COO^- in case of Cu^{2+} (basic conditions)

–1 point if COO^- and Cu^0

–1 point if COO (uncharged) and Cu^{2+}

0 point if both NH_2 coordinated

–2 points if not neutral

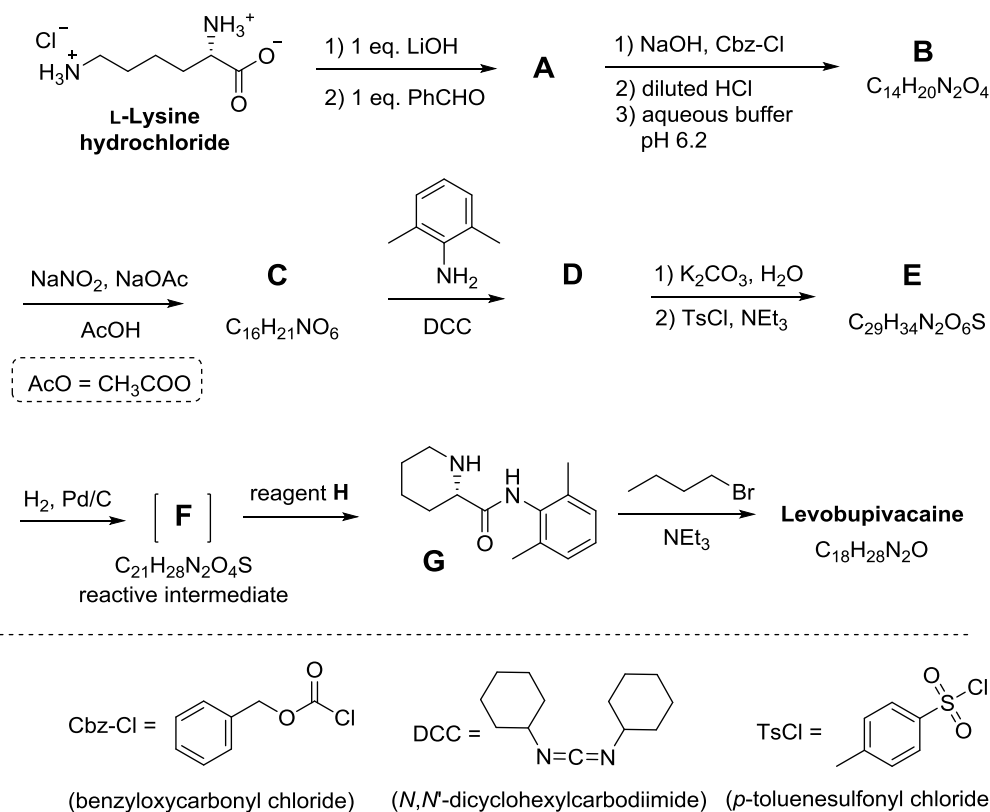
One or two molecules of water may be coordinated

One or two HO^- may be coordinated if the overall charge is correct

0 points if the ligand is not bidentate or if only one or more than two molecules of L-lysine are coordinated.

Total: 4 points

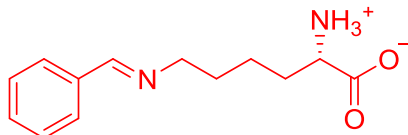
Fortunately, in the synthesis of levobupivacaine shown below, the same amino group reacts even without Cu^{2+} salt.



From this point on, you can use the abbreviations proposed in the scheme above.

4. **Draw** the structure of compound **A**, including the appropriate stereochemistry.

A



3 points for the correct structure (both *E* and *Z* isomers accepted).

–1 point if stereochemistry is wrong or missing.

–1 point if the overall charge is not zero.

–1 point if hemiaminal instead of imine.

–1 point if two equivalents of LiOH were used.

–2 points if α -amino group was transformed into imine.

0 point if both amino groups were transformed into imines.

Full score if ϵ coordinated in Q3 and α protected in Q4

Total: 3 points

5. Transformation of L-lysine into **A** is (**choose** proper answer(s)):

an enantioselective reaction.

an enantiospecific reaction.

a regioselective reaction.

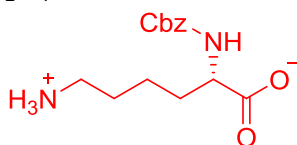
2 points.

0 point if any incorrect answer.

Total: 2 points

6. **Draw** the structures of compounds **B–F**, including the appropriate stereochemistry.

B C₁₄H₂₀N₂O₄



3 points

No penalty if ϵ -Cbz protected lysine starting from α -imine.

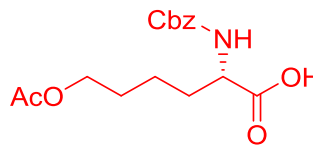
–1 point if stereochemistry is wrong or missing, unless already penalized in the previous structure.

–1 point if overall charge is not neutral.

0 point if ϵ NH₂ protected from ϵ imine.

0 point if α NH₂ protected from α imine.

C C₁₆H₂₁NO₆

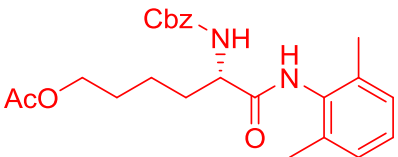

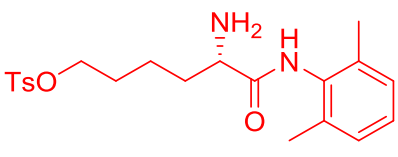


4 points

No penalty if correct transformation of α -amino group starting from ϵ -Cbz protected lysine.

–1 point if stereochemistry is wrong or missing, unless already penalized in the previous structure.

–2 points if alcohol instead of acetate.

<p>D</p>  <p>3 points -1 point if stereochemistry is wrong or missing, unless already penalized in the previous structure. 0 point if Cbz is cleaved in this step. 0 point if Ac is cleaved in this step, unless no Ac in the previous structure.</p>	<p>E $C_{29}H_{34}N_2O_6S$</p>  <p>3 points -1 point if stereochemistry is wrong or missing, unless already penalized in the previous structure. 0 point if Cbz is cleaved in this step. 0 point if Ac is cleaved in this step, unless no Ac in the previous structure.</p>
<p>F $C_{21}H_{28}N_2O_4S$</p>  <p>4 points -1 point if stereochemistry is wrong or missing, unless no Ac in the previous structure. 0 point if Ts is cleaved.</p>	<p>Total: 17 points</p>

7. What is the role of DCC in the transformation **C** → **D**?

- Protecting group for the amino group.
 Protecting group for the hydroxy group.
 Activating agent for the amide bond formation.

Total: 1 point

8. TsCl is used in the synthesis to enable:

- Nucleophilic substitution of an amino group.
 Electrophilic substitution of an amino group.
 Nucleophilic substitution of a hydroxy group.
 Electrophilic substitution of a hydroxy group.

Total: 1 point

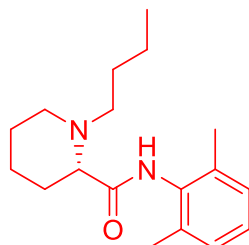
9. **Mark** all possible reagents which could be used as reagent **H**:

- | | |
|---|--|
| <input type="checkbox"/> diluted HCl | <input type="checkbox"/> Zn/HCl |
| <input checked="" type="checkbox"/> K_2CO_3 | <input type="checkbox"/> H_2SO_4 |
| <input type="checkbox"/> diluted $KMnO_4$ | <input checked="" type="checkbox"/> diluted NaOH |
| <input type="checkbox"/> $SOCl_2$ | <input type="checkbox"/> PCl_5 |

1 point for each correct answer.
 -1 point for each incorrect answer.
 The total score in question 9 may not be negative.
Total: 2 points

10. **Draw** the structure of levobupivacaine, including the appropriate stereochemistry.

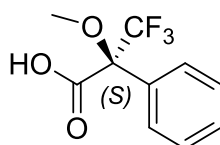
Levobupivacaine $C_{18}H_{28}N_2O$



4 points
 -1 point if stereochemistry is wrong or missing
 -2 points if amide is alkylated instead of amine
Total: 4 points

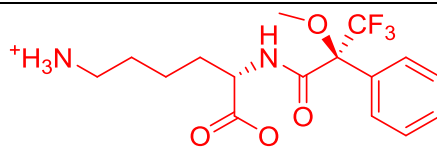
Part II.

The synthesis of levobupivacaine requires the use of enantiomerically pure L-lysine. A common method to confirm the enantiomeric purity of aminoacids is their transformation into amides using Mosher's acid (see the structure of the (*S*) isomer below).



(*S*)-Mosher's acid

11. **Draw** the structure of the amide formed when the α -amino group of L-lysine is derivatized with (*S*)-Mosher's acid. Clearly show the stereochemistry of each chiral center.



2 points (neutral as well as zwitterionic forms accepted)
 -1 point for each stereogenic center if stereochemistry is wrong or missing.
 -1 point if total charge is not neutral.
 No penalty if ϵ NH_2 instead of α NH_2 .
Total: 2 points

12. **How many products** will be formed from racemic lysine and (*S*)-Mosher's acid (consider that only the α -amino group of lysine is derivatized)?

- Two diastereoisomers.
- Four diastereoisomers.
- A racemic mixture of two enantiomers.
- Four compounds: two enantiomers and two diastereoisomers.

Total: 2 points

13. **Choose** the method(s) which can be used to quantitatively determine the enantiomeric purity of lysine after its derivatization with (*S*)-Mosher's acid:

- NMR spectroscopy.
- Liquid chromatography.
- Mass spectrometry.
- UV-vis spectroscopy.

1 point for each correct answer.

-1 point for each incorrect answer.

The total score in question 13 may not be negative.

Total: 2 points