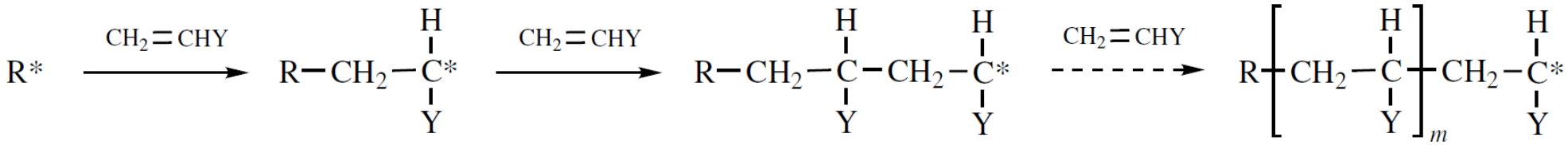
Ring-Opening Polymerization

16:160:509 – Polymer Chemistry

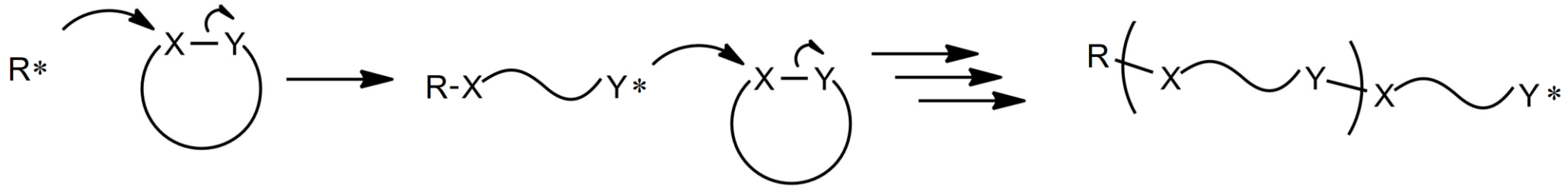
Lecture 13 to 14

RUTGERS
School of Arts and Sciences
DEPARTMENT OF CHEMISTRY
AND CHEMICAL BIOLOGY

Another Way of Achieving Chain-Growth Polymerization



Other than opening double bonds, are there alternative ways of achieving chain-growth polymerization?



If a propagating chain can open a ring and regenerate the propagating center, then repeating this process will lead to chain-growth polymerization. This is known as ring-opening polymerization (ROP).

The driving force in vinyl polymerization comes from forming a σ bond in exchange for a π bond. What is the driving force of ring-opening polymerization?

ROP Is Driven by the Release of Ring Strain

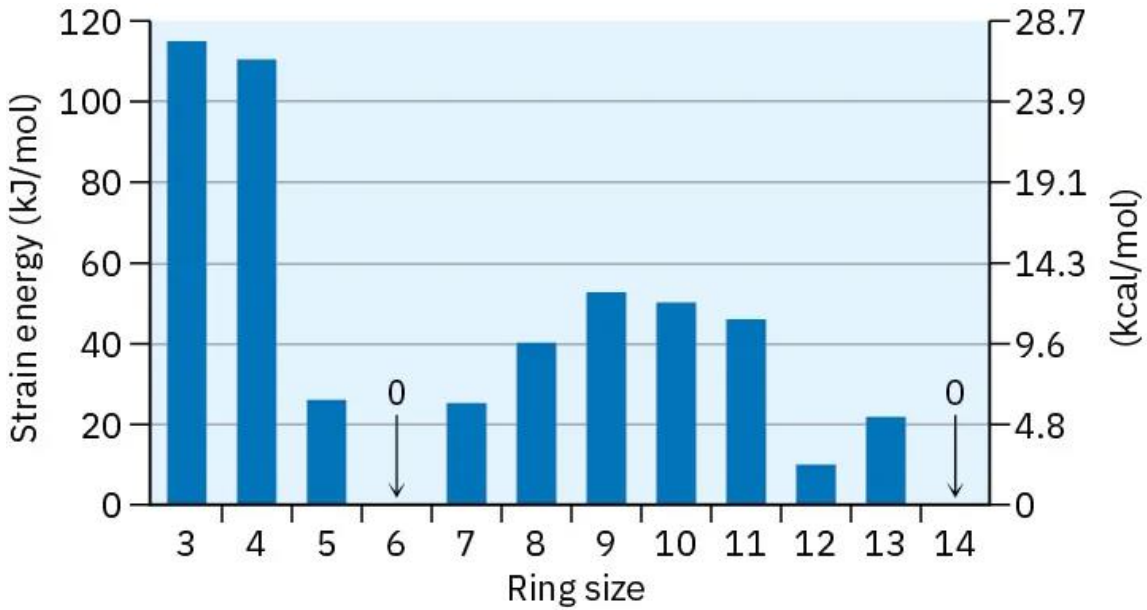
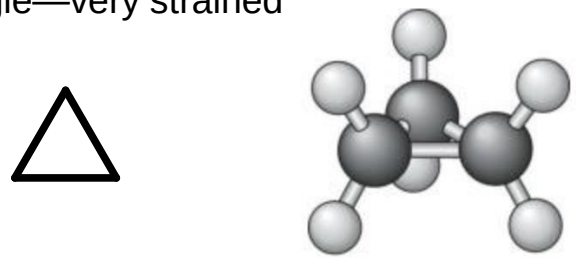


TABLE 7-1 Thermodynamics of Polymerization of Cycloalkanes at 25°C

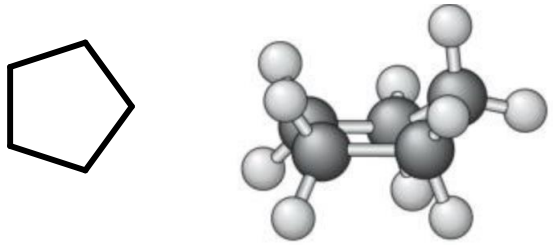
$(CH_2)_n$ n	ΔH_{lc} (kJ mol^{-1})	ΔS_{lc} (J mol^{-1} K^{-1})	ΔG_{lc} (kJ mol^{-1})
3	−113.0	−69.1	−92.5
4	−105.1	−55.3	−90.0
5	−21.2	−42.7	−9.2
6	+2.9	−10.5	+5.9
7	−21.8	−15.9[a]	−16.3
8	−34.8	−3.3[a]	−34.3

60° angle—very strained

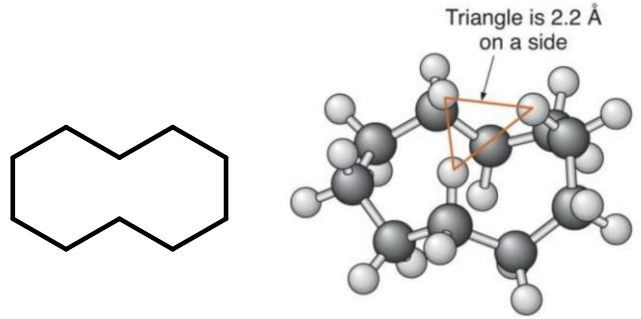


Angle strain

Eclipsed bonds



Torsional strain



Transannular strain

Anionic ROP of Ethylene Oxide

ROP may proceed via an anionic or a cationic mode (the two most common ways for ROP):

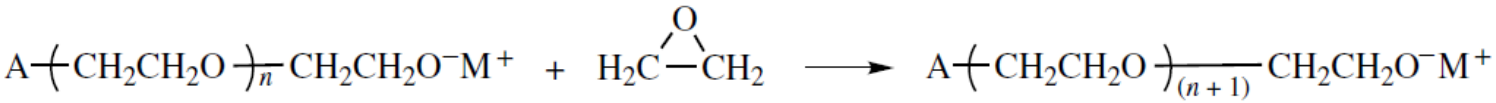
Let's take ROP of ethylene oxide as an example:

1. Anionic ROP of ethylene oxide

Initiation:

M^+A^- = metal alkyls, hydroxides, alkoxides, sodium naphthalene, etc.

Propagation:

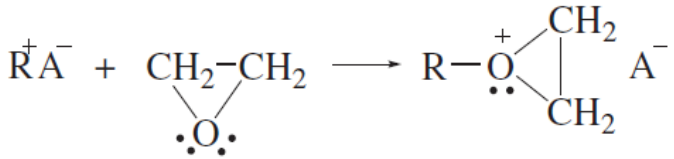


The reaction shares all the features we have learned about anionic polymerization, including proceeding as a **living polymerization** (in the absence of a proton source) and having a **narrow molecular weight distribution**. Propagation may occur via ion pairs or free ions. It was measured that $k_p^{\mp} \approx 0.025$ L mol^{-1} s^{-1}, $k_p^{-} \approx 1.67$ L mol^{-1} s^{-1}, which is **much slower than that in the anionic polymerization of vinyl monomers** (compare with Slide 14 in Lecture 9)—a common feature of ROP.

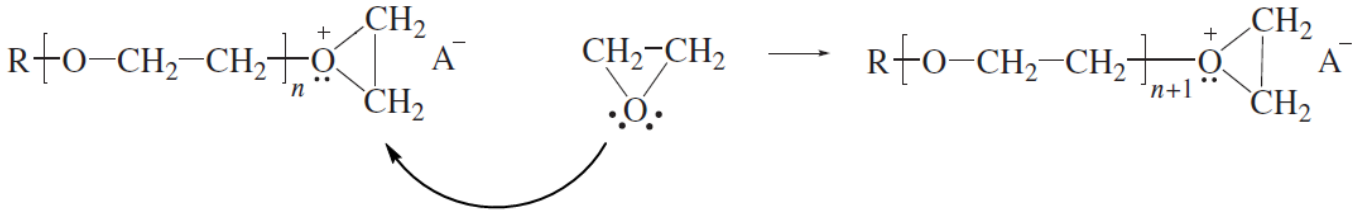
Cationic ROP of Ethylene Oxide

2. Cationic ROP of ethylene oxide

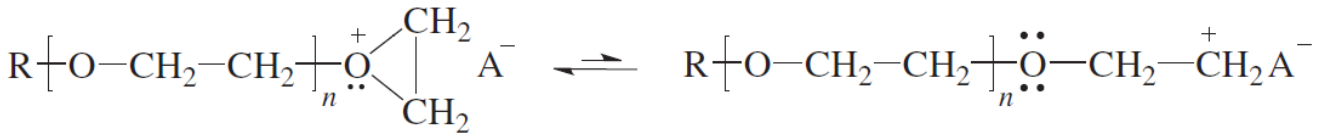
Initiation:



Propagation:

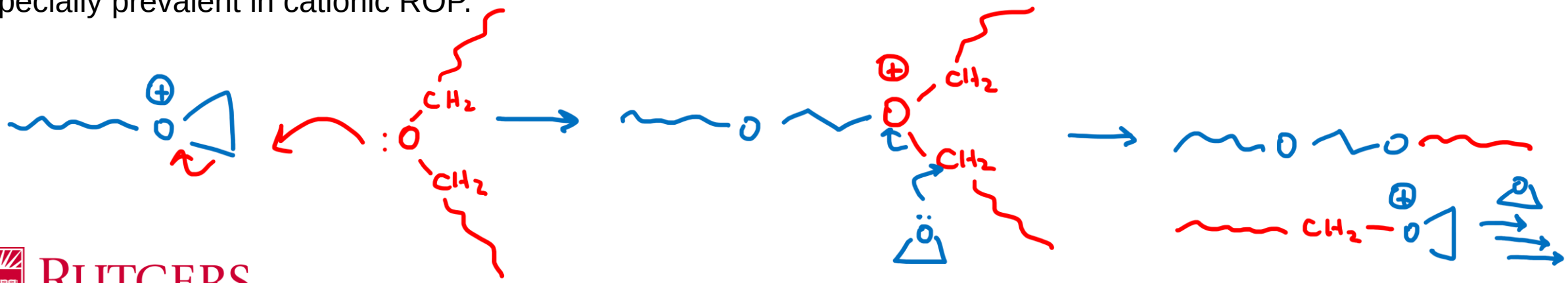


R^+A^- = CF_3COOH, CF_3SO_3H, $BF_3{\cdot}H_2O$,$SbCl_5{\cdot}HCl$, etc.

cyclic oxonium ion  open-chain carbocation

Equilibrium much more favored to the left

Similar to other cationic polymerizations, chain transfer and termination do occur. Chain transfer to polymers is especially prevalent in cationic ROP.



Anionic Coordination ROP of Ethylene Oxide

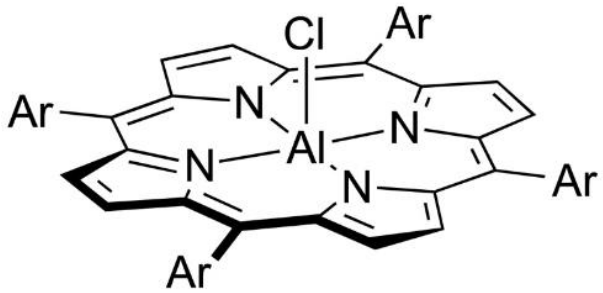
3. Anionic coordination ROP of ethylene oxide

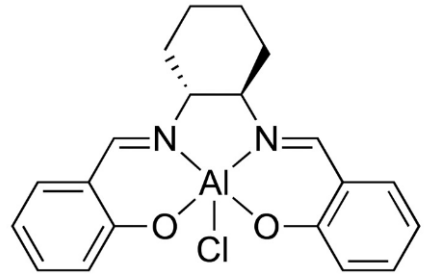
Can we combine the benefits of anionic ROP (better chain-end control—livingness) and cationic ROP (more reactive chain end—faster reaction) in one system?

$Zn(OMe)_2$

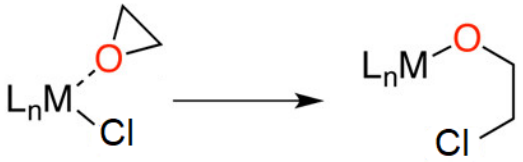
$ClFe[OCH(CH_3)CH_2Cl]_2$

$[(RO)_2AlO]_2Zn$

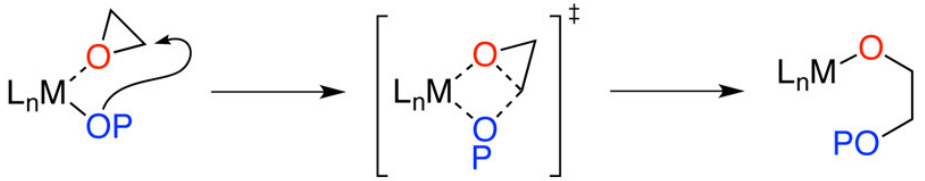




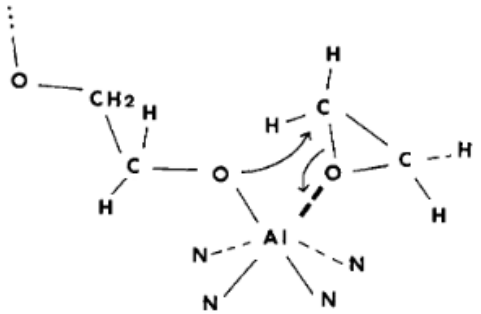
Initiation:



Propagation:

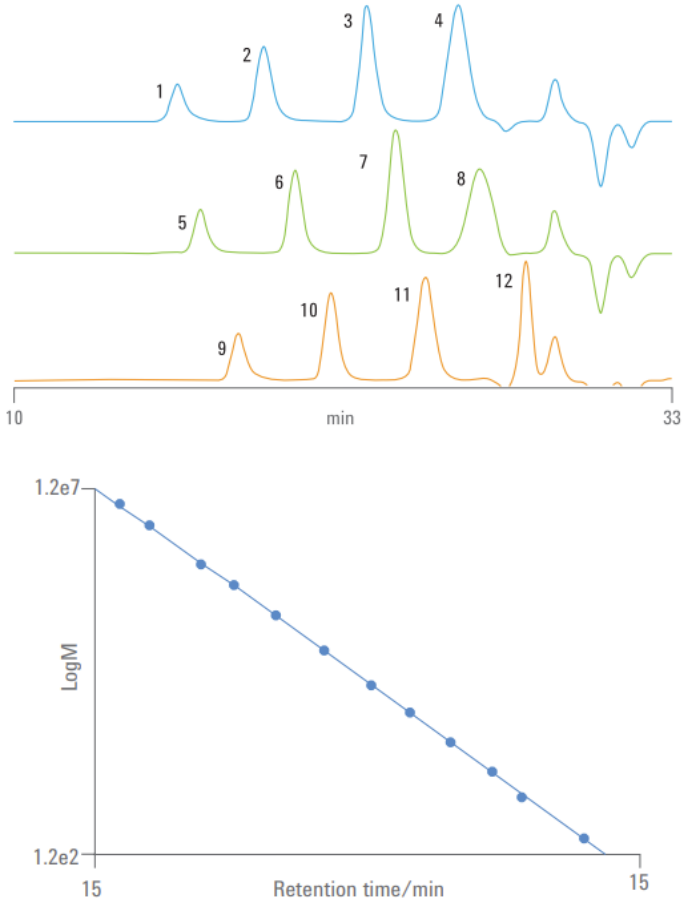


- The metal center has two roles:
  1. Associates with the anionic chain ends to minimize side reactions
  2. Coordinates with the monomer to make it more reactive
- Anionic coordination ROP results in fast and living polymerization of high-molecular weight poly(ethylene oxide)

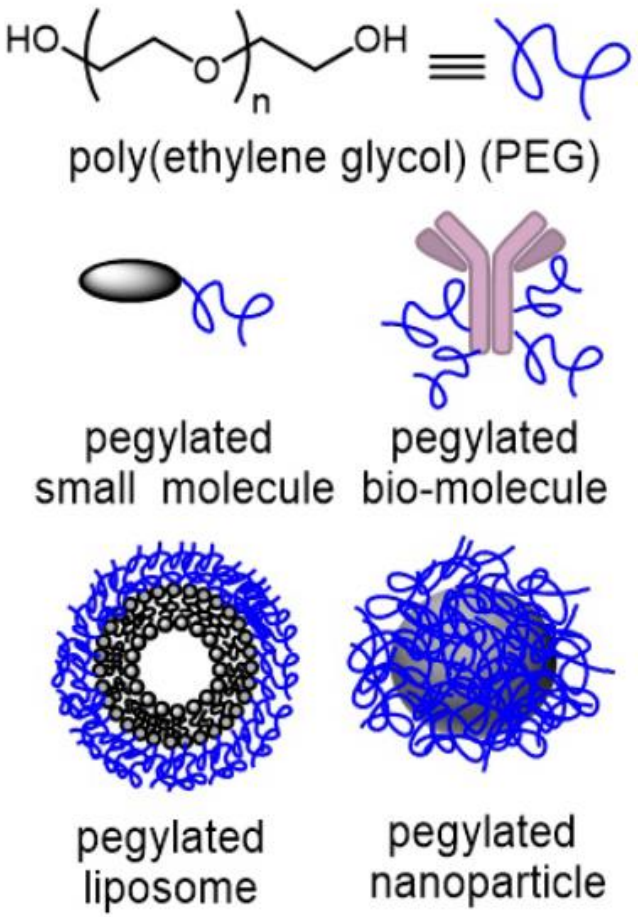


Childers, M. I.; Longo, J. M.; Van Zee, N. J.; LaPointe, A. M.; Coates, G. W., *Chem. Rev.* **2014,** *114*, 8129-8152.

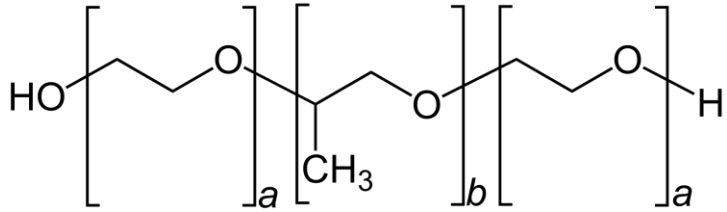
Application of Polymers and Copolymers of Ethylene Oxide



PEG-based GPC standards (very narrow distribution)



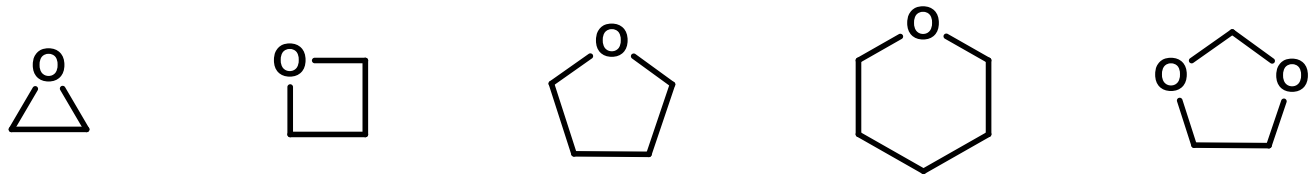
PEGylation (attach PEGs to therapeutic molecules to improve their safety and efficiency)



Poloxamer (PEO-*b*-PPO-*b*-PEO)

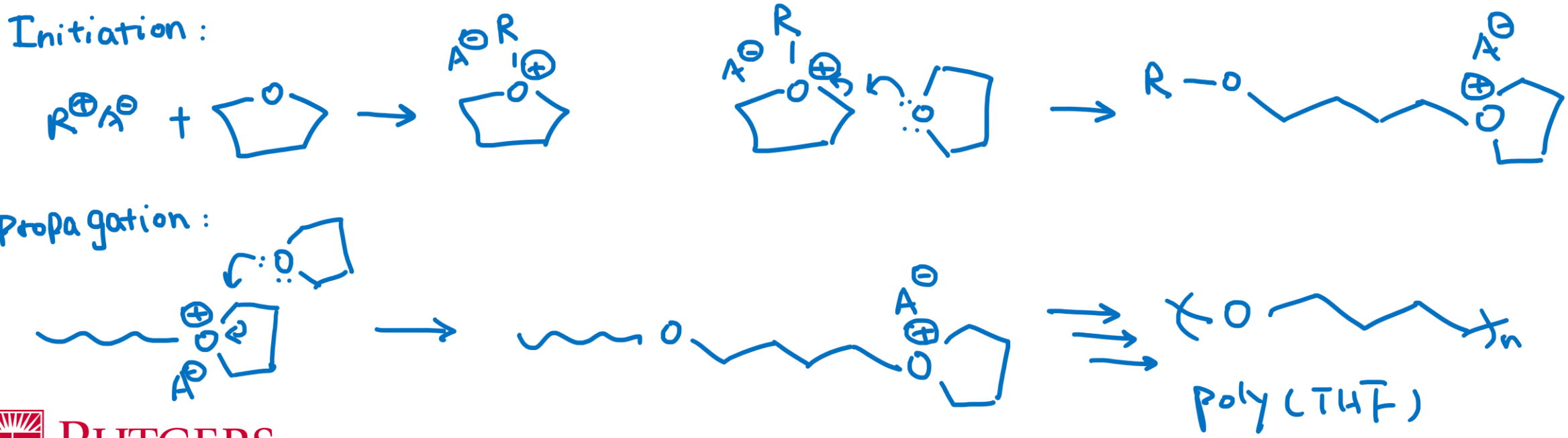
First block copolymers to become commercially available (used as surfactants, cell culture media)

ROP of Other Cyclic Ethers or Acetals



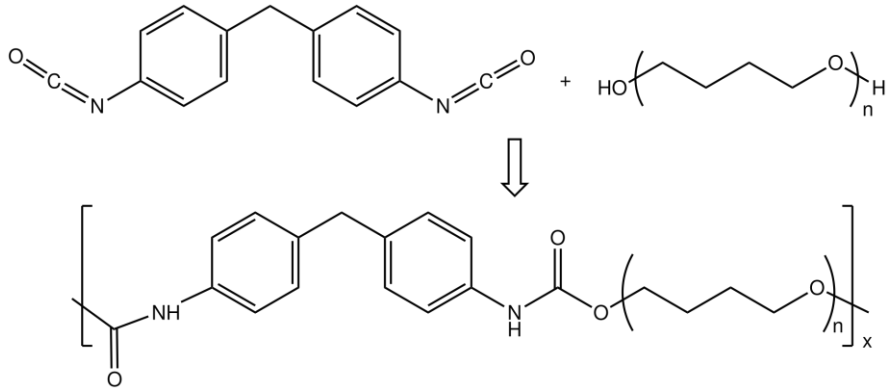
Anionic ROP	✓	×	×	×	×
Cationic ROP	✓	✓	✓	×	✓

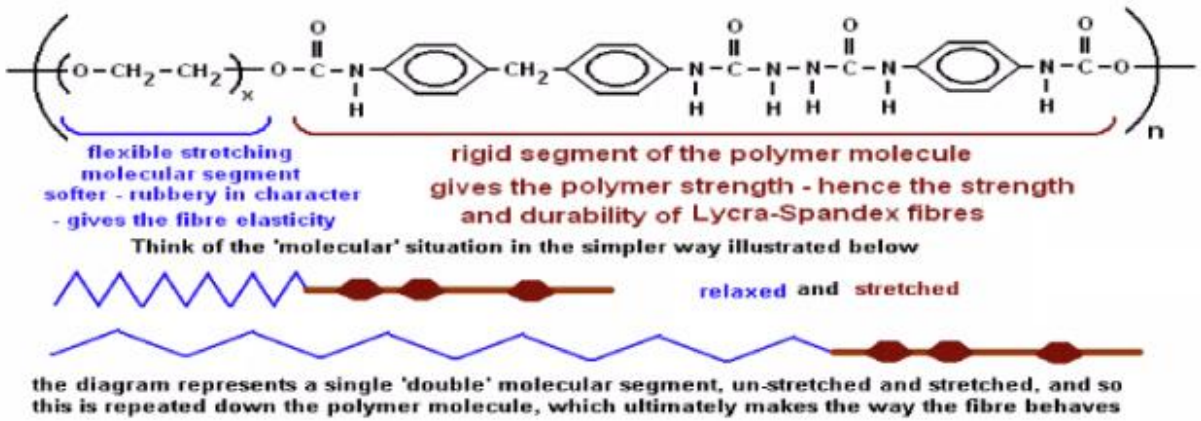
The cationic ROP of other cyclic ethers or acetals follows a similar mechanism as ethylene oxide:



Commercial Use of PolyTHF

Polytetrahydrofuran is commercially available (e.g., PolyTHF® by BASF) as polymers with low average molecular weights (below 3,000 Da). The major use of such polyTHF is as monomers (“macrodiols”) in further step-growth polymerization to make polyurethane-based elastomers.



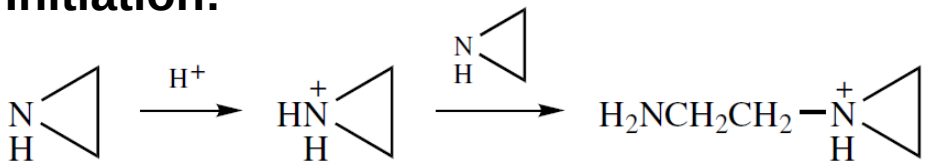


Spandex (invented by Joseph Shivers at DuPont in 1958)

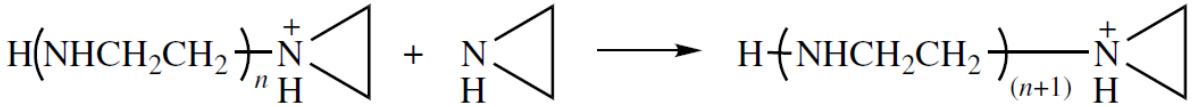
Cationic ROP of Aziridine

Aziridine

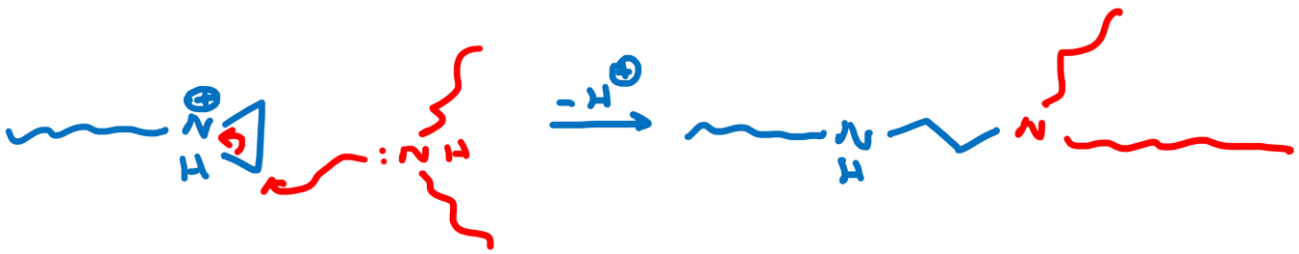
Initiation:

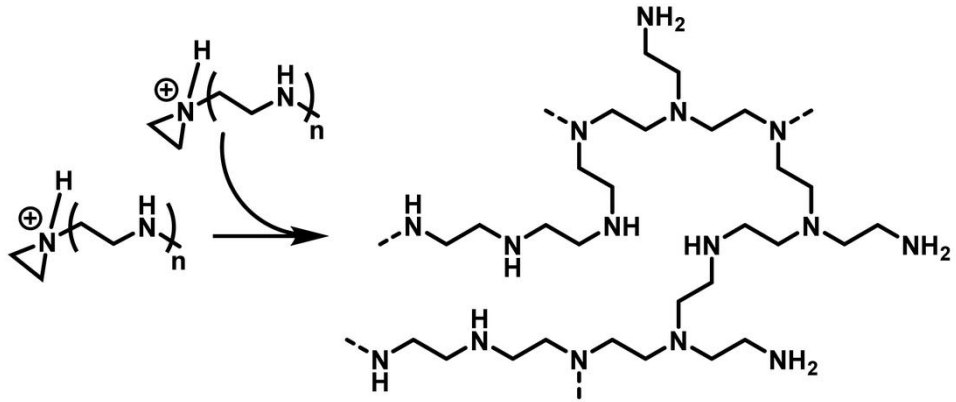


Propagation:

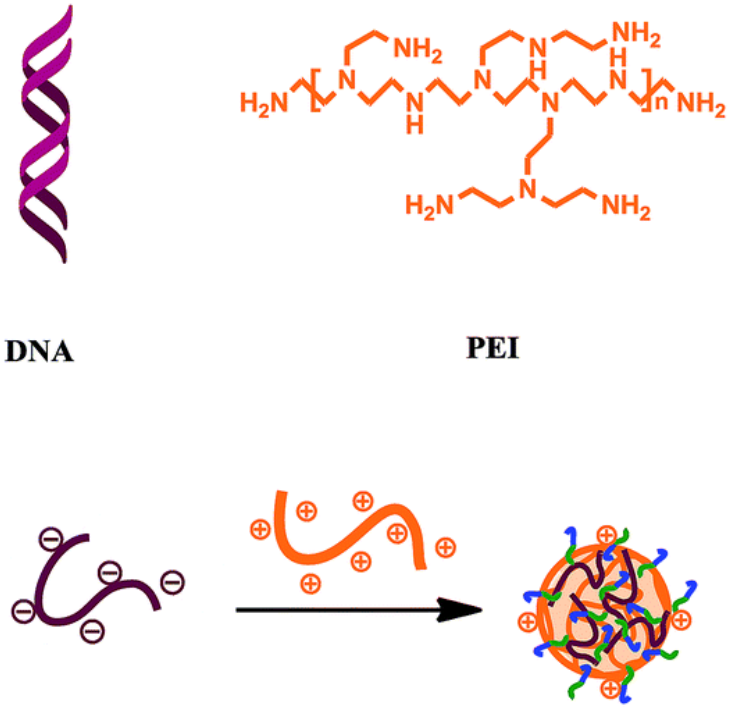


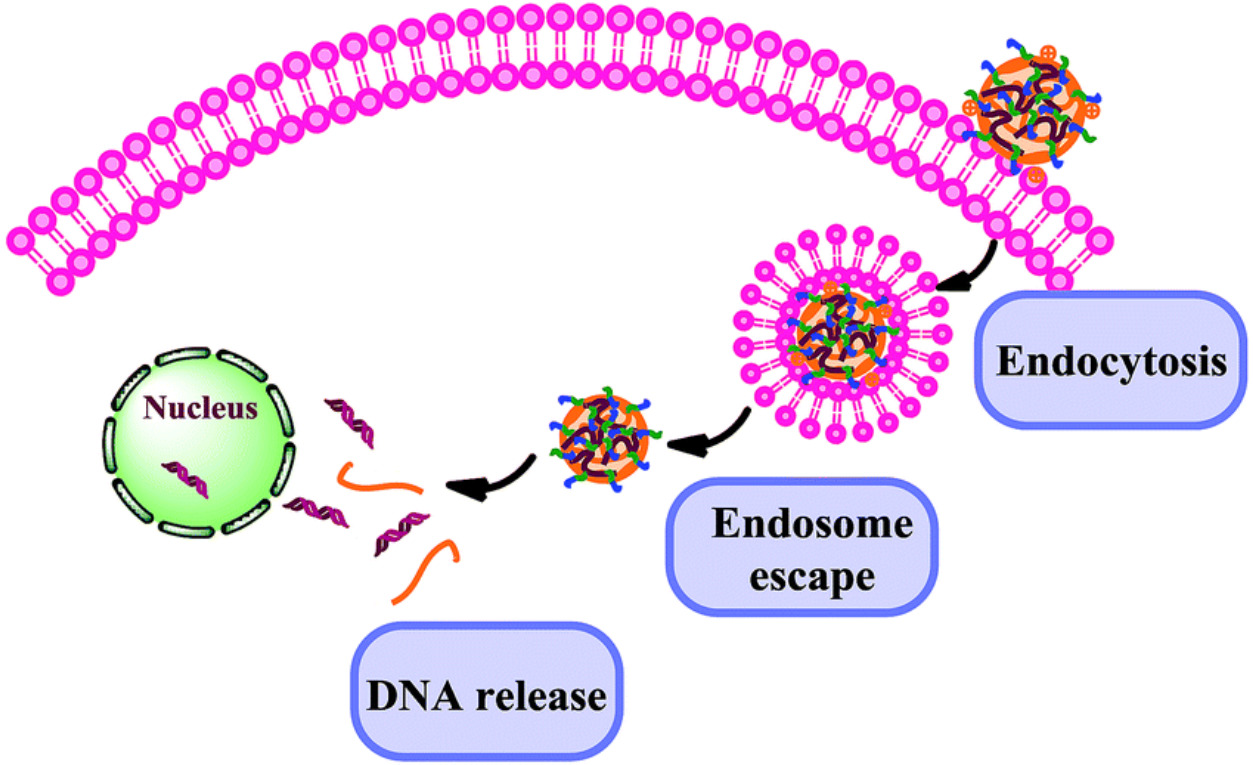
- Aziridine can be easily polymerized via cationic ROP but is unreactive toward anionic polymerization as an amine anion is never a good leaving group in organic chemistry.
- A process similar to chain transfer in the ROP of cyclic ethers occurs extensively in the ROP of aziridine, leading to branches (instead of chain transfer). Eventually, we get a branched polymer polyethylenimine (PEI).





Biomedical Application of Polyethylenimine

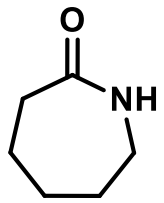




PEI is highly positively charged and may form a polymer-DNA complex (polyplex) with negatively charged nucleic acids. This makes PEI one of the most used transfecting agents for gene/plasmid delivery.

Boussif, O.; Lezoualc'h, F.; Zanta, M. A.; Mergny, M. D.; Scherman, D.; Demeneix, B.; Behr, J. P., *Proc. Natl. Acad. Sci. USA* **1995,** *92*, 7297-7301.

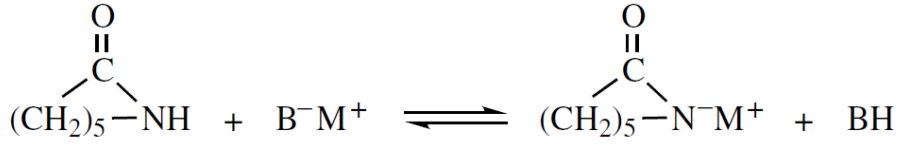
Anionic ROP of Lactam

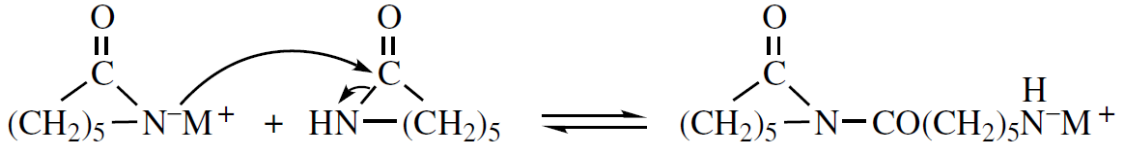


Caprolactam

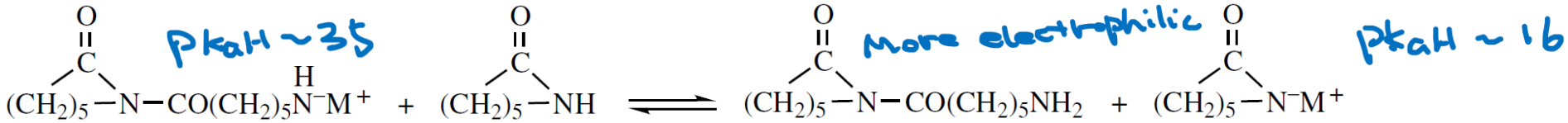
While lactam can be polymerized via cationic initiators, the conversion and polymer molecular weight are often low (refer to Page 570 in Odian if you are interested in the mechanism). Anionic initiation of lactam works well. The most important lactam monomer is caprolactam, which is polymerized commercially to give Nylon 6.

Initiation:



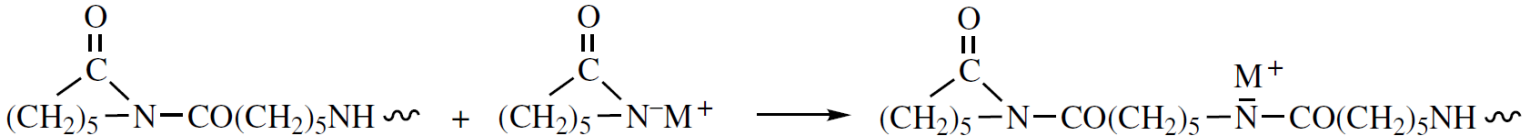


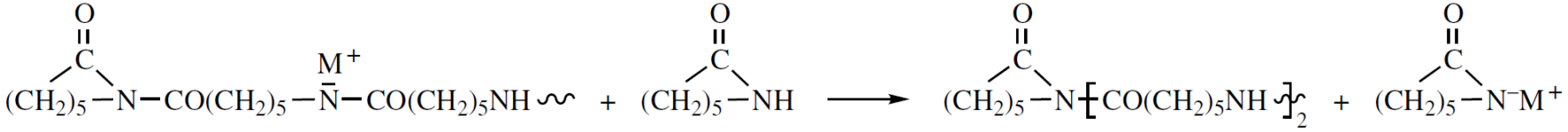
B^-M^+ = metal hydrides, metal amides, metal alkoxides, etc.



Actual initiating species

Propagation:

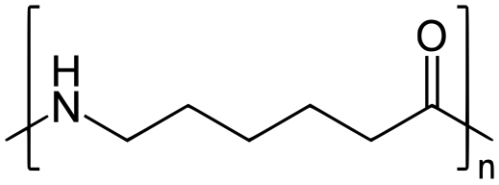




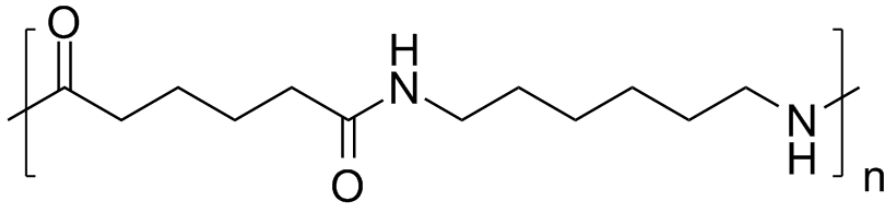
Activated monomer

"Activated monomer mechanism" (notice how it is different from the regular anionic ROP)

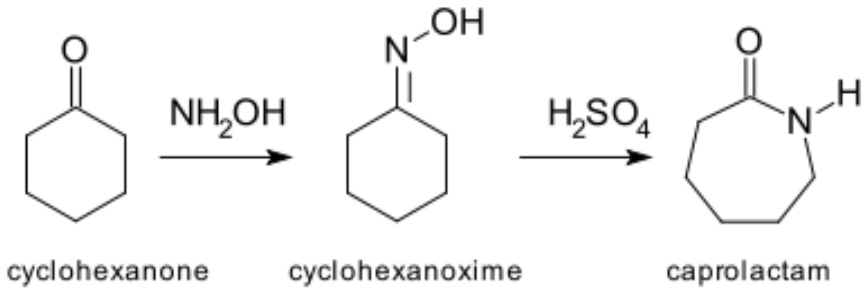
Nylon 6



Nylon 6 (polycaprolactam)



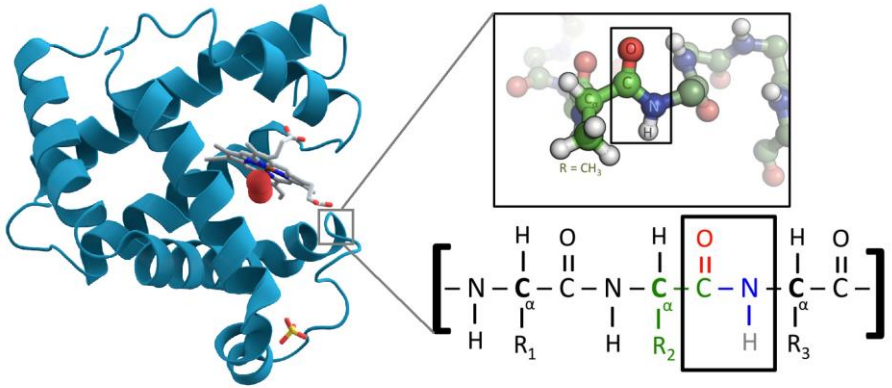
Nylon 66

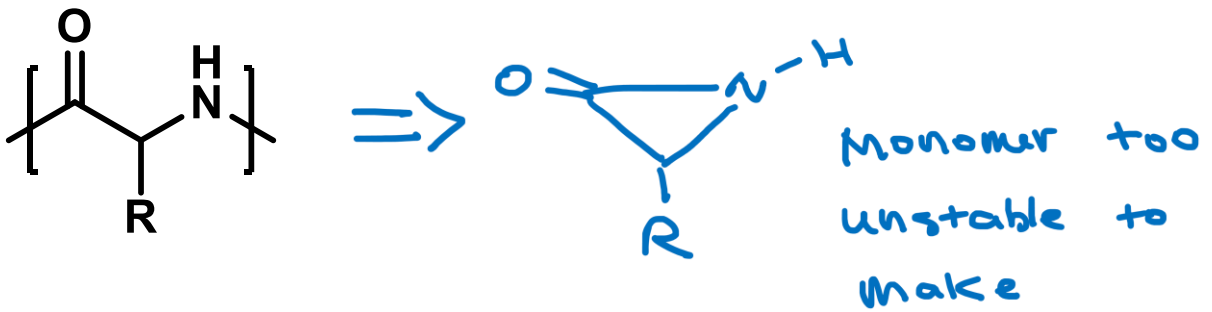


Easy access to the monomer
via Beckmann Rearrangement

- Nylon 6 has similar properties and usage as Nylon 66 (in fact, it was developed in 1938 to reproduce the properties of Nylon 66 without violating the patent on its production).

ROP of *N*-Carboxyanhydrides (NCAs)

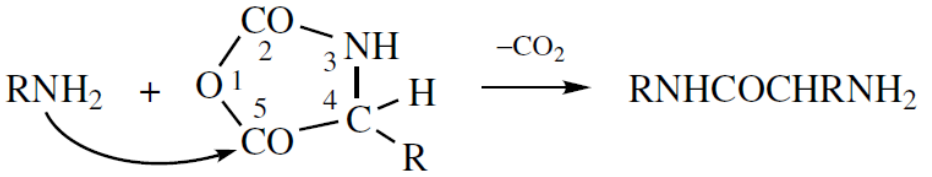


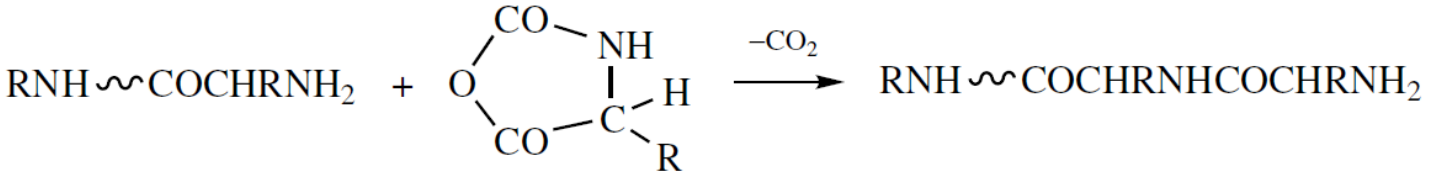


Polypeptides are a special class of polyamides. Can they be synthesized via ROP?

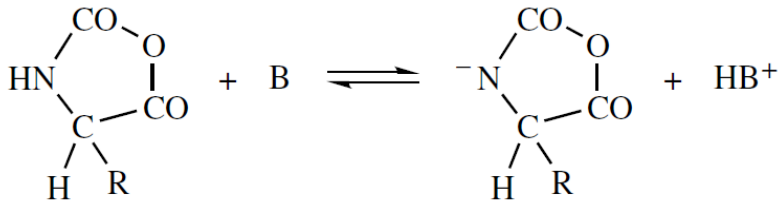
Different Initiators Result in Different Mechanisms

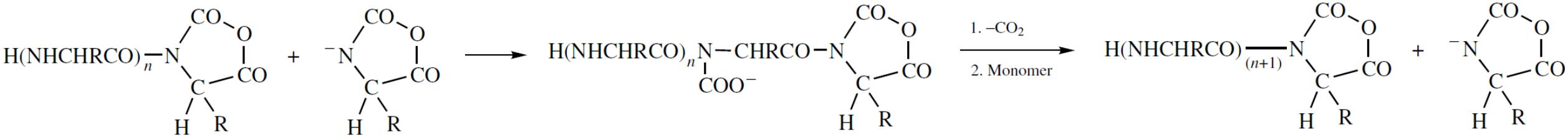
1. Normal amine mechanism (NAM)—initiated by primary amine





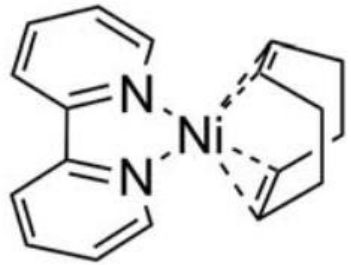
2. Activated monomer mechanism (AMM)—initiated by strong base (e.g., OH^-, RO^-) or tertiary amine



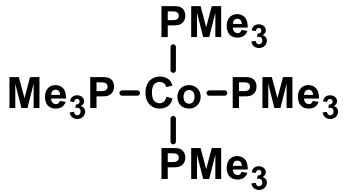


Different Initiators Result in Different Mechanisms

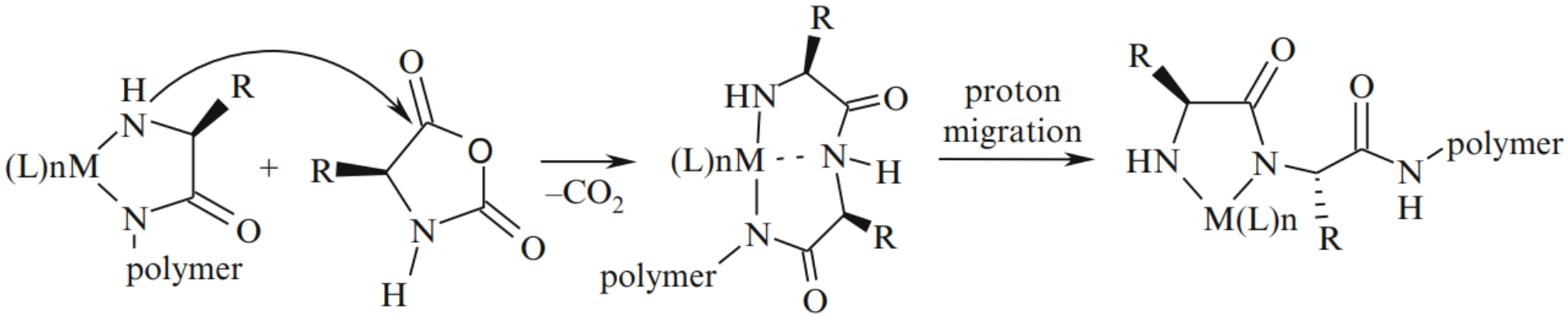
3. Coordination insertion mechanism—initiated by transition metal compounds



(bipy)Ni(cod)



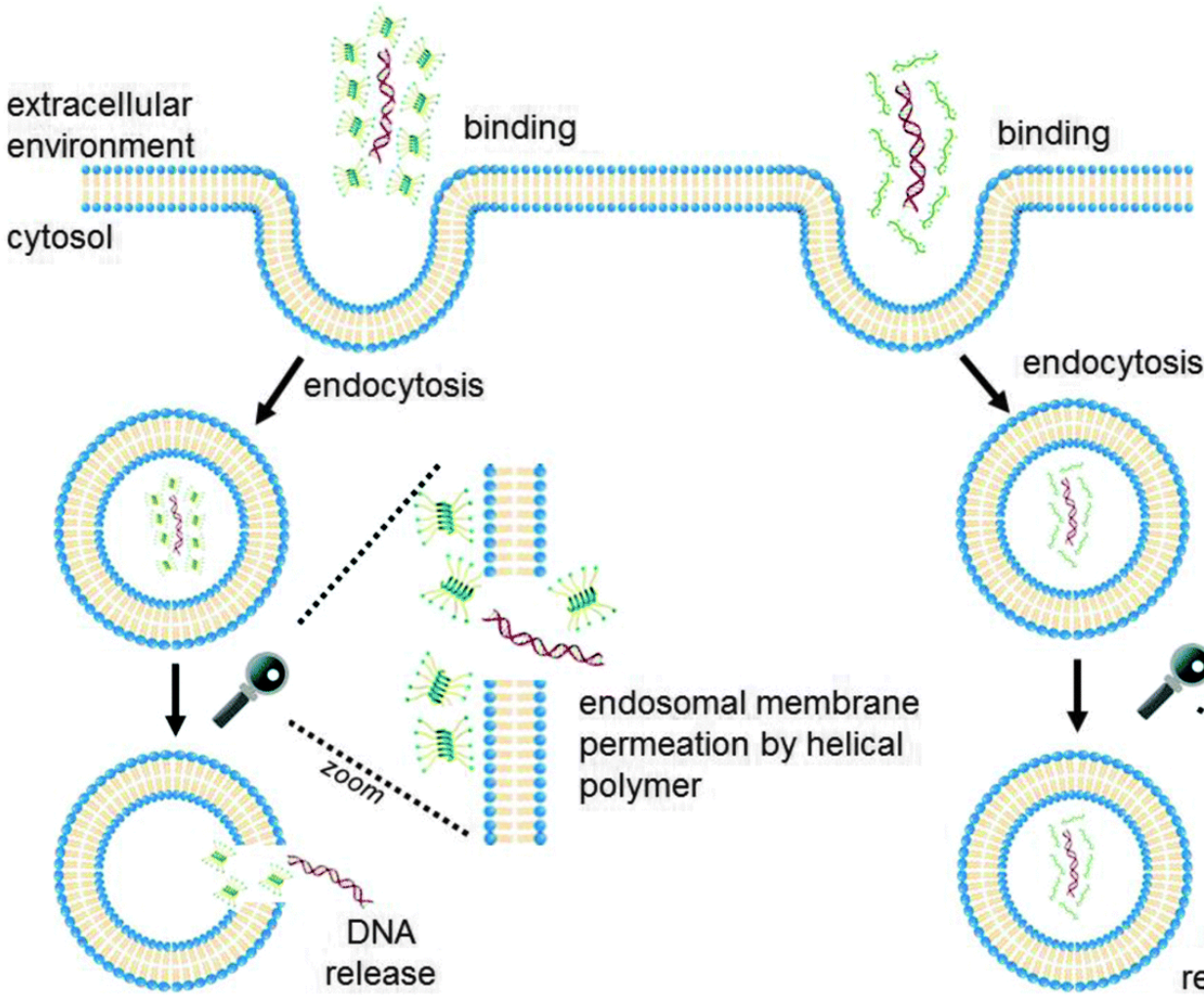
$(PMe_3)_4Co$

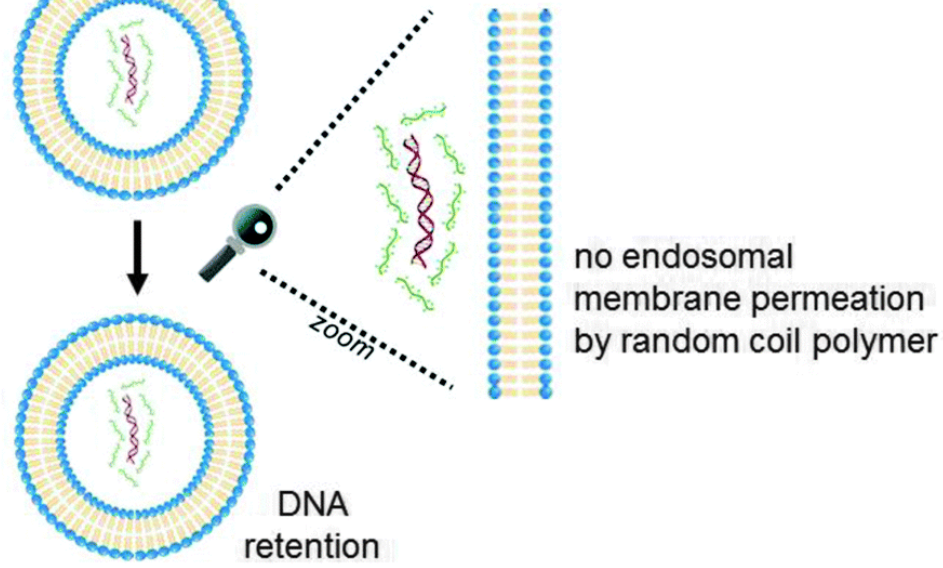


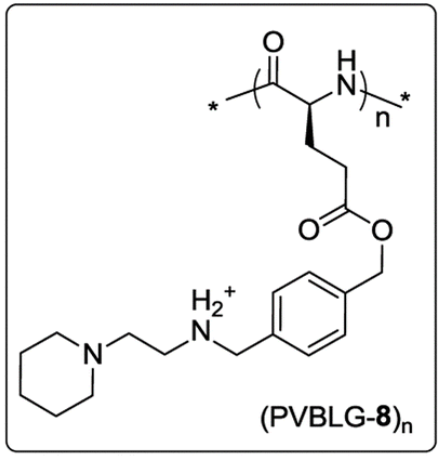
Transition-metal initiated ROP of NCA provides better control and demonstrates livingness by minimizing side reactions associated with NAM or AMM.

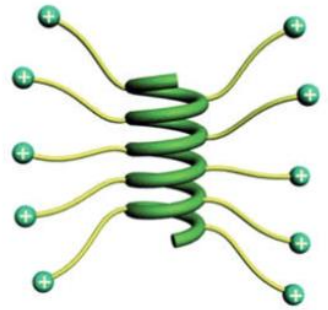
Deming, T. J., *Nature* **1997,** *390*, 386-389.

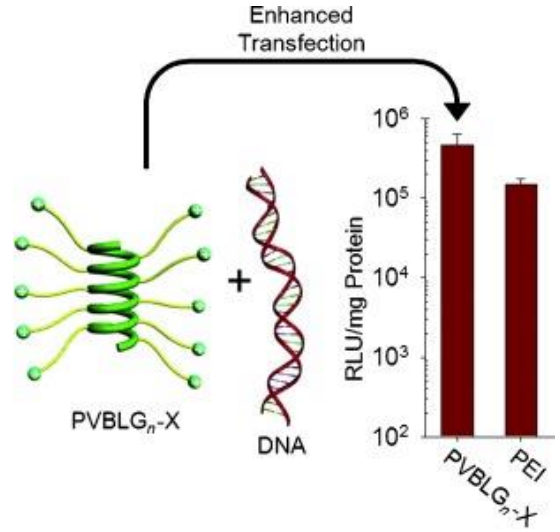
Synthetic Polypeptides via NCA Lead to Various Biomedical Applications





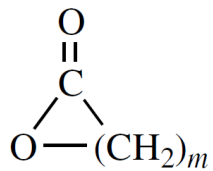


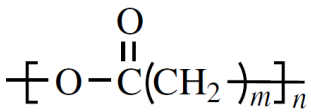




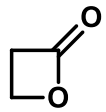
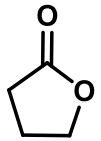
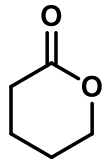
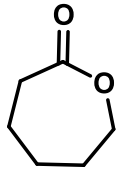
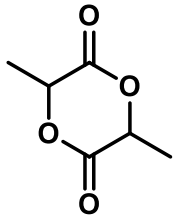
Gabrielson, N. P.; Lu, H.; Yin, L.; Li, D.; Wang, F.; Cheng, J., *Angew. Chem. Int. Ed.* **2012,** *51*, 1143-1147.

Thermodynamics of Lactone Ring-Opening Polymerization





$$T_c = \frac{\Delta H^\circ}{\Delta S^\circ + R \ln [\mathrm{M}]_c}$$

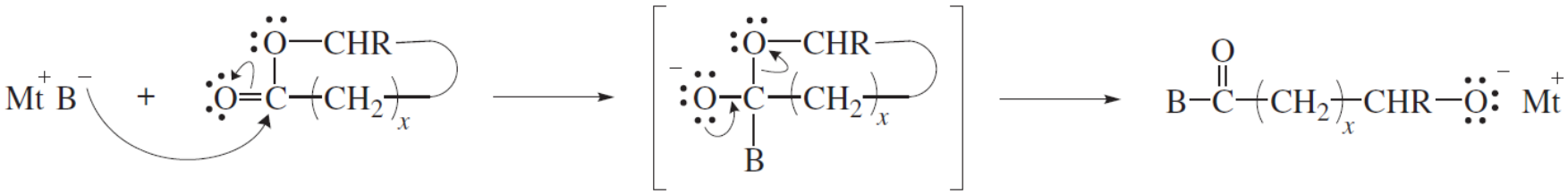
	ΔH_p^0 (kJ · mol^{-1})	ΔS_p^0 (J · mol^{-1} · K^{-1})	T_c for [M] = 1 mol · L^{-1}
β-Propiolactone 	-75.0	-54.0	1116 °C
γ-Butyrolactone 	-5.4	-39.6	-137 °C
δ-Valerolactone 	-12.2	-28.6	154 °C
ε-Caprolactone 	-28.8	-35.9	530 °C
Lactide 	-22.9	-41.4	280 °C

Olsén, P.; Odelius, K.; Albertsson, A.-C., *Biomacromolecules* **2016,** *17*, 699-709.
Save, M.; Schappacher, M.; Soum, A., *Macromol. Chem. Phys.* **2002,** *203*, 889-899.

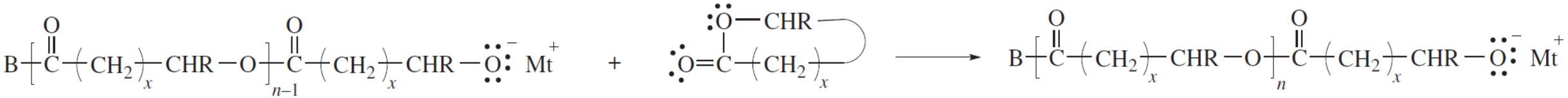
Anionic ROP of Lactone

Cationic ROP of lactone often fails to produce high molecular weight polymers (refer to Page 583 in Odian for mechanism), whereas anionic ROP of lactone works well.

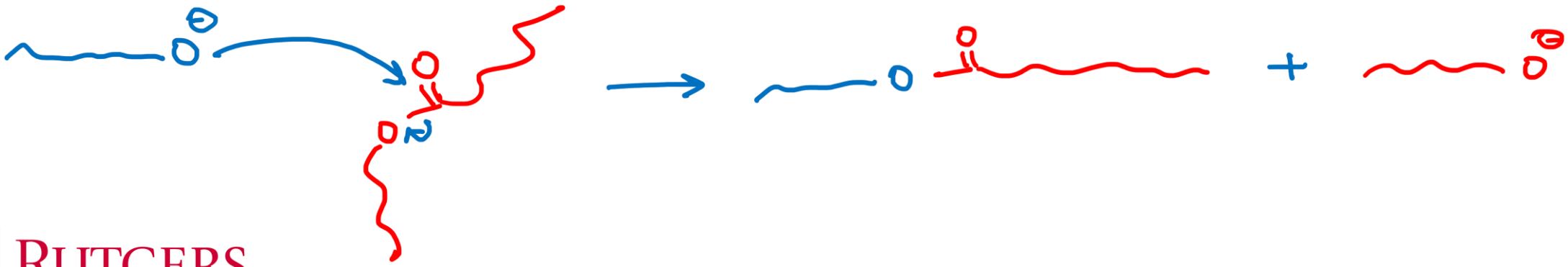
Initiation:



Propagation:



Chain transfer due to transesterification occurs in the anionic ROP of lactone, resulting in a broadening of molecular weight distribution.

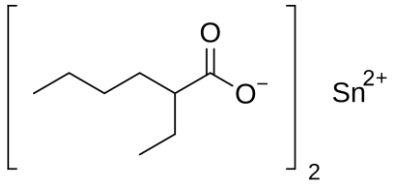


Coordination ROP of Lactone

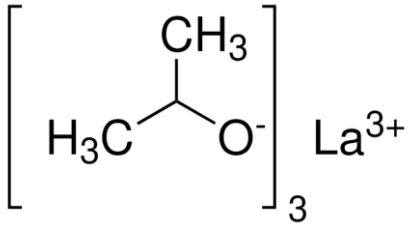
To minimize chain transfer, one strategy is to use coordination polymerization, where the reactivity of chain ends is controlled by the coordinated metal centers.

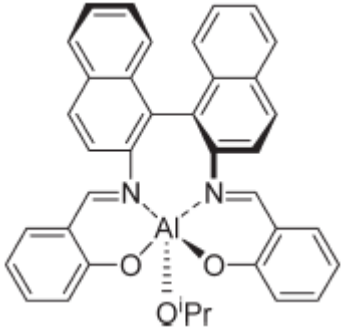
Examples of common coordination initiators for the ROP of lactone:

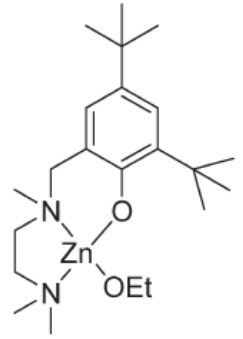
$Sn(Oct)_2$/ROH

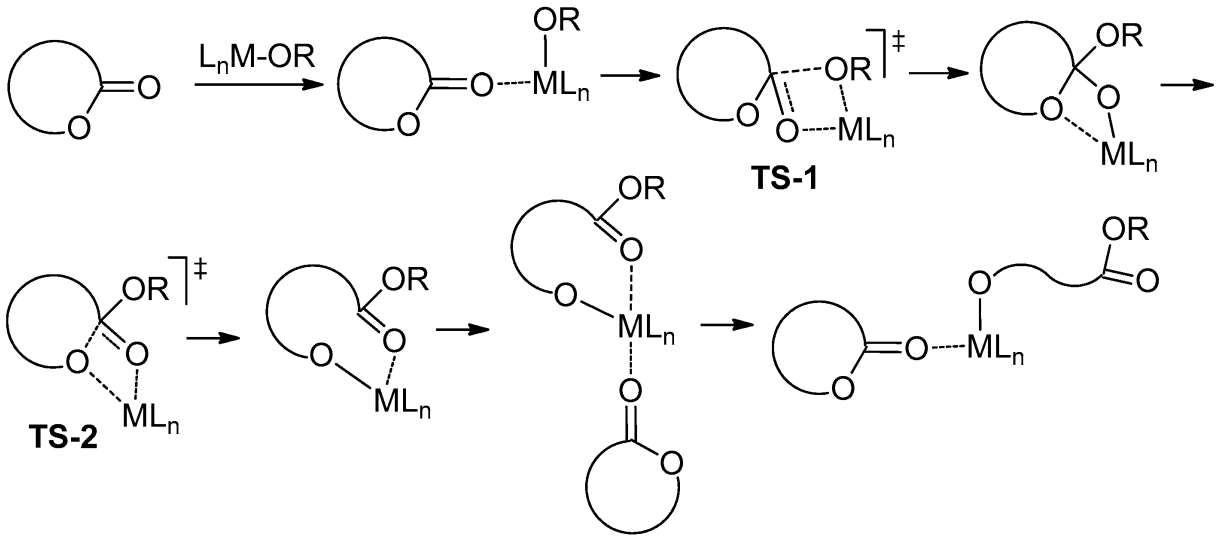


$Sn(OR)_2$ being the actual initiating species





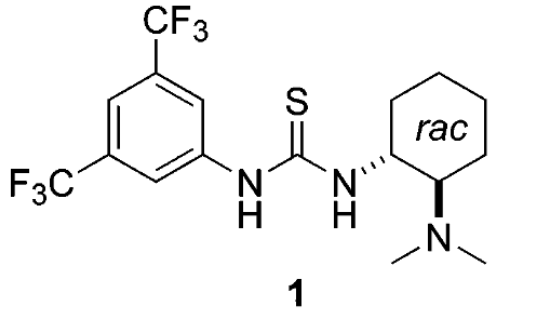




Nifant'ev, I.; Ivchenko, P., *Molecules* **2019,** *24*, 4117.

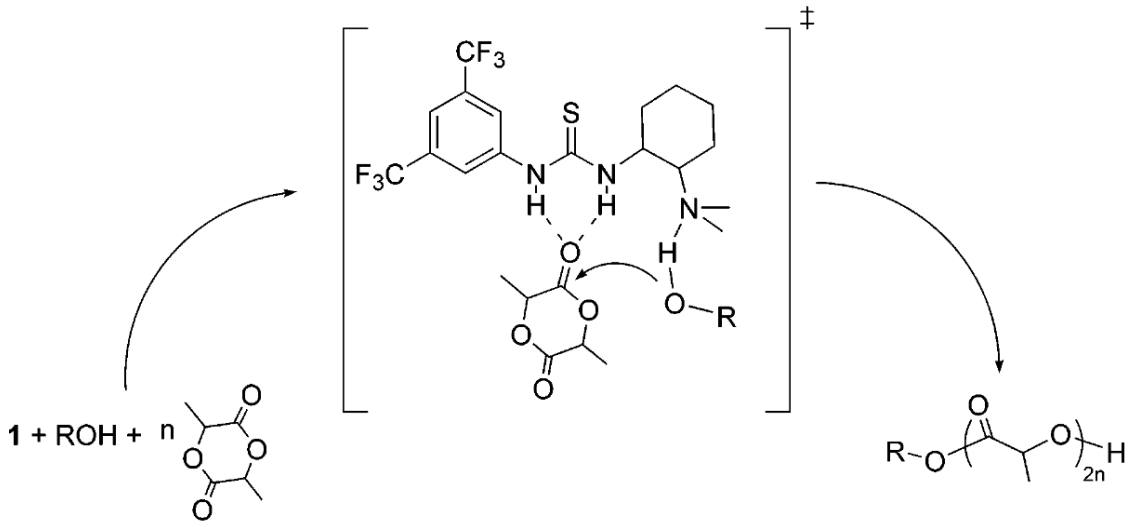
Organic Catalysis for ROP of Lactone

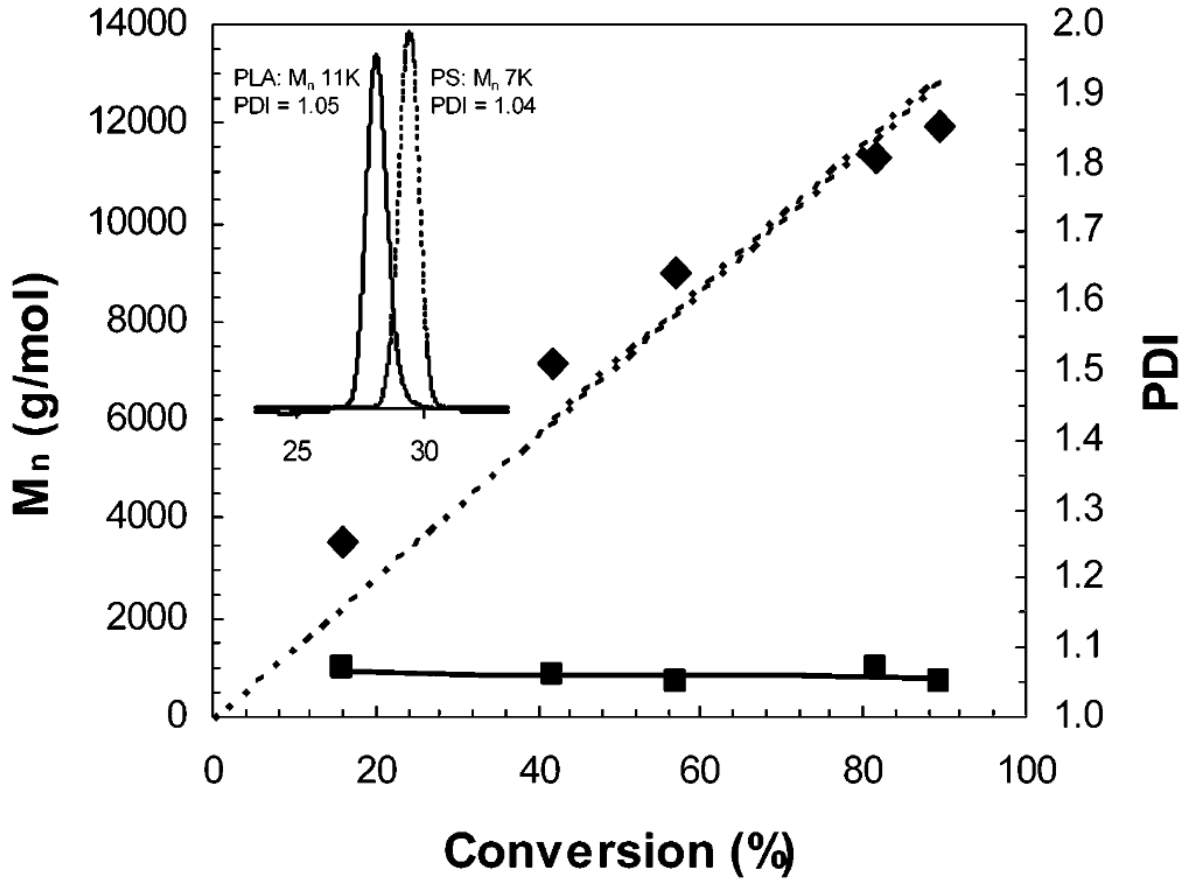
Coordination to a metal center is not the only way to enable chain-end control. Several organic catalysts have been developed over the past 20 years for the ROP of lactone.



1

Thiourea-Amine Catalyst

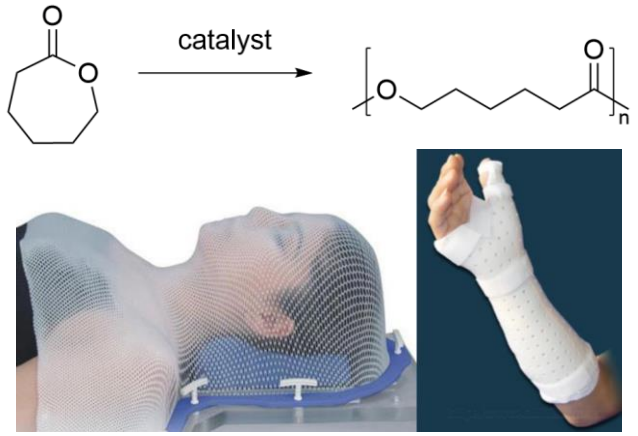




Dove, A. P.; Pratt, R. C.; Lohmeijer, B. G. G.; Waymouth, R. M.; Hedrick, J. L., *J. Am. Chem. Soc.* **2005,** *127*, 13798-13799.

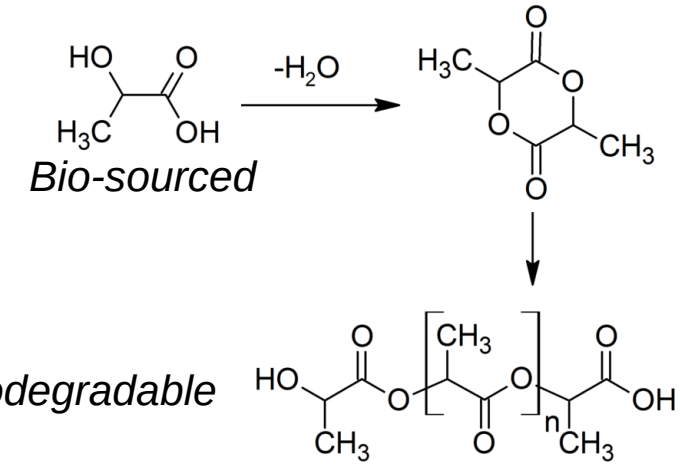
Some Important Applications of Lactone-Derived Polymers

Polycaprolactone (PCL)

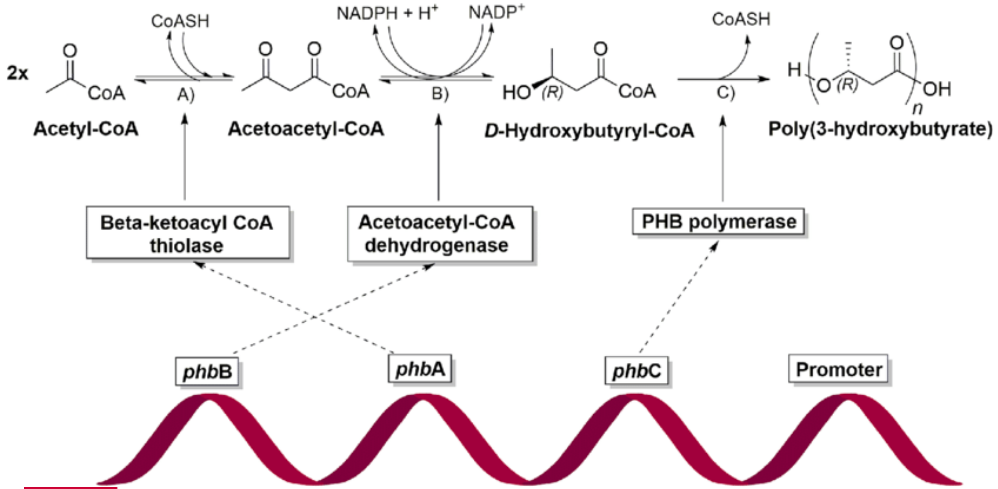


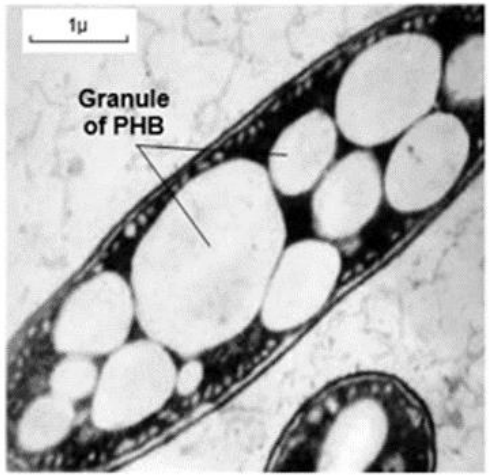
Splinting

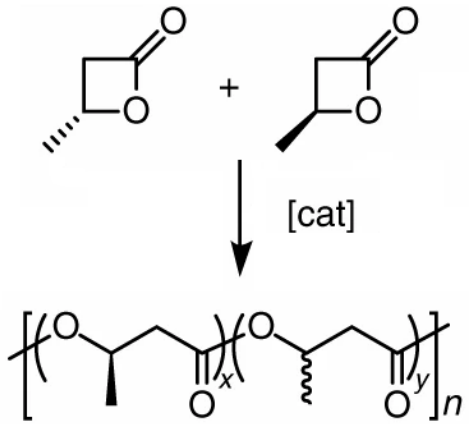
Polylactide (PLA)



Polyhydroxybutyrate (PHB)

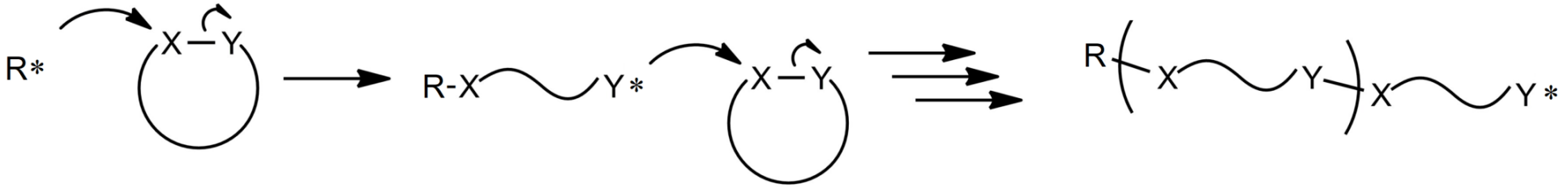






PHBs are biopolymers produced by a variety of organisms

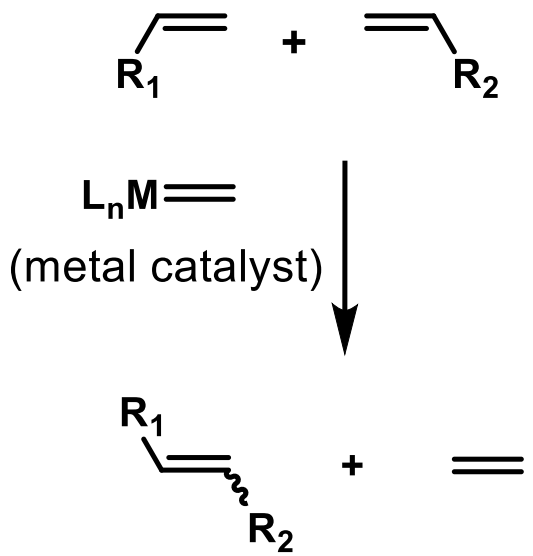
Is Cationic or Anionic Mode the Only Way to Achieve ROP?

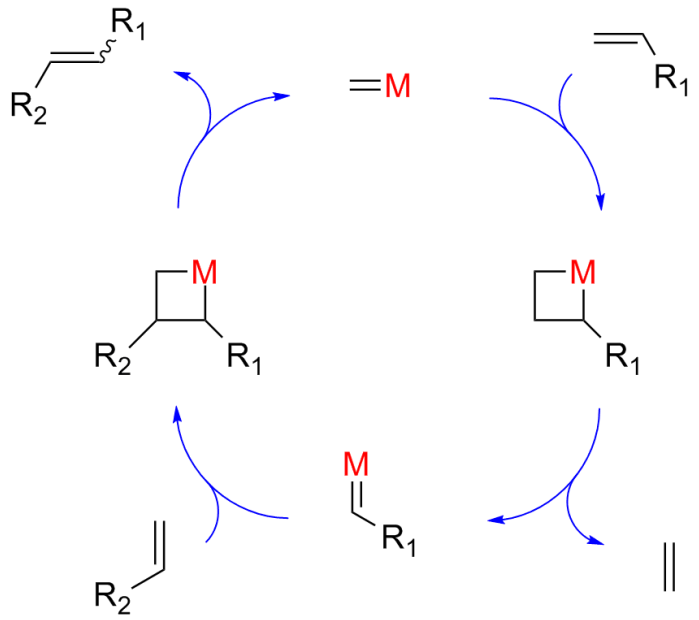


To ensure a working ROP, we need:

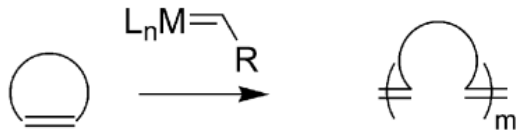
- The cyclic monomer to have sufficient ring strain to be easily opened.
- Opening of cyclic monomers to regenerate the propagating chain end.

Let's first learn a reaction that might not be familiar to you—**olefin metathesis**.

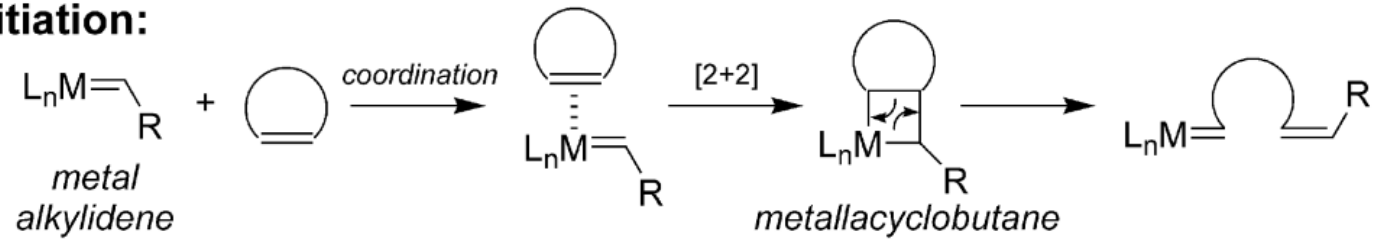




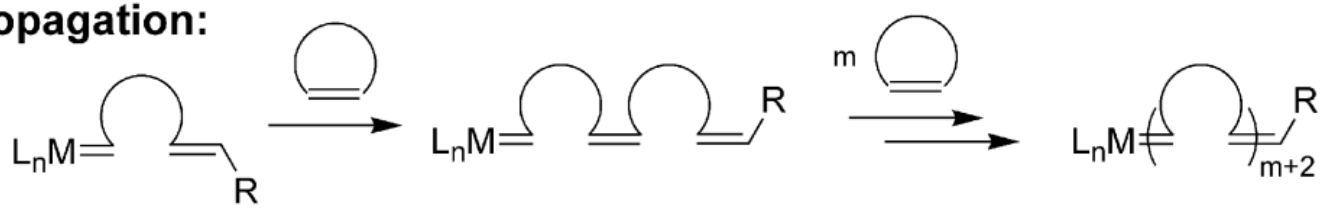
Ring-Opening Metathesis Polymerization (ROMP)



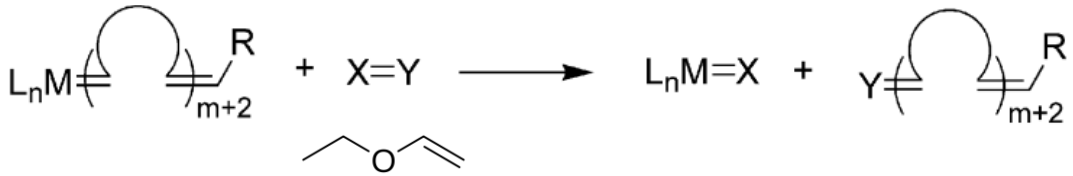
Initiation:



Propagation:

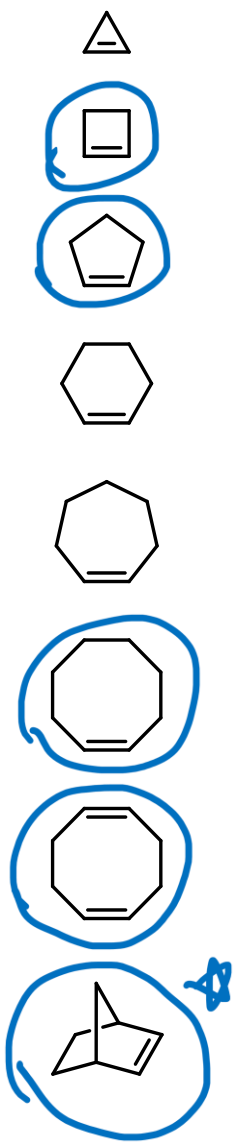


Termination:



Ethyl vinyl ether

Ring strain energy ($kJ \cdot mol^{-1}$)

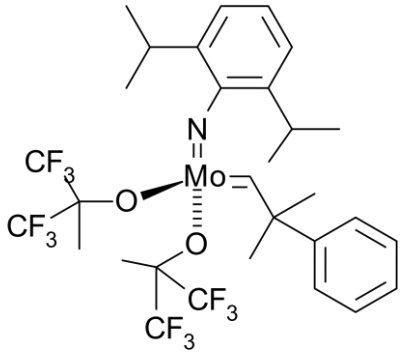


△	228.0	✓
□	128.0	✓
⬠	28.5	✓
⬡	10.5	✗
⯃	28.0	✓
⯄	31.0	✓
⯄	55.6	✓
⯅	113.8	✓

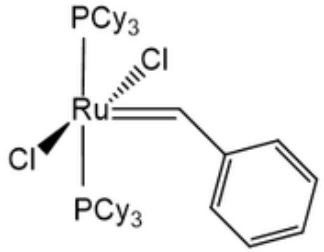
Neary, W. J.; Kennemur, J. G., *ACS Macro Lett.* **2019,** *8*, 46-56.

ROMP Catalysts

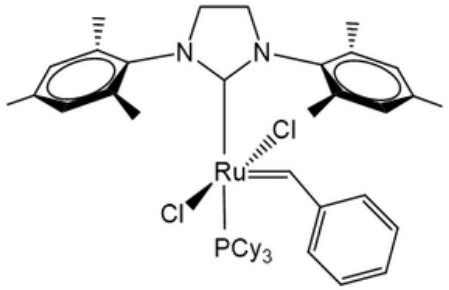
- Heterogeneous catalysts such as $WCl_6/AlEt_3$, $TiCl_4/LiAlR_4$, $MoCl_5/Et_3Al$, and $RuCl_3/HCl$ (ROMP of norbornene and cyclooctene was discovered in the 1950s in industry without knowledge of the mechanisms of these reactions).
- Various homogeneous catalysts have been developed since the 1980s, primarily led by Richard Schrock at MIT and Robert Grubbs at Caltech. These catalysts provide better control for ROMP processes and enable a better understanding of the reaction mechanism. Below are some examples of homogeneous catalysts used in ROMP.



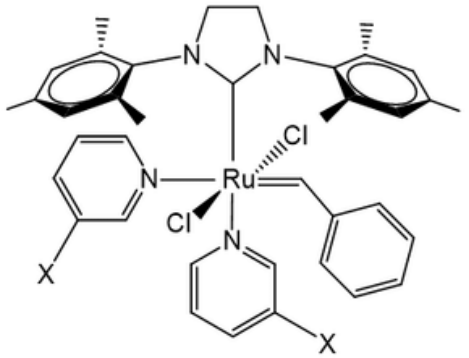
Schrock catalyst



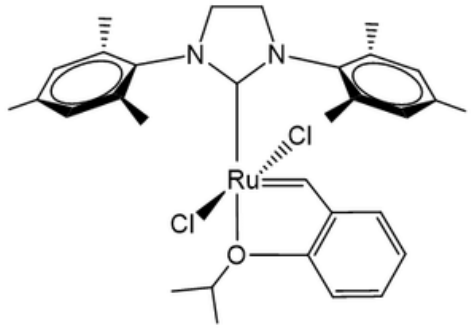
G1
(Grubbs catalyst,
1st generation)



G2
(Grubbs catalyst,
2nd generation)



G3 (X = H or Br)
(Grubbs catalyst,
3rd generation)

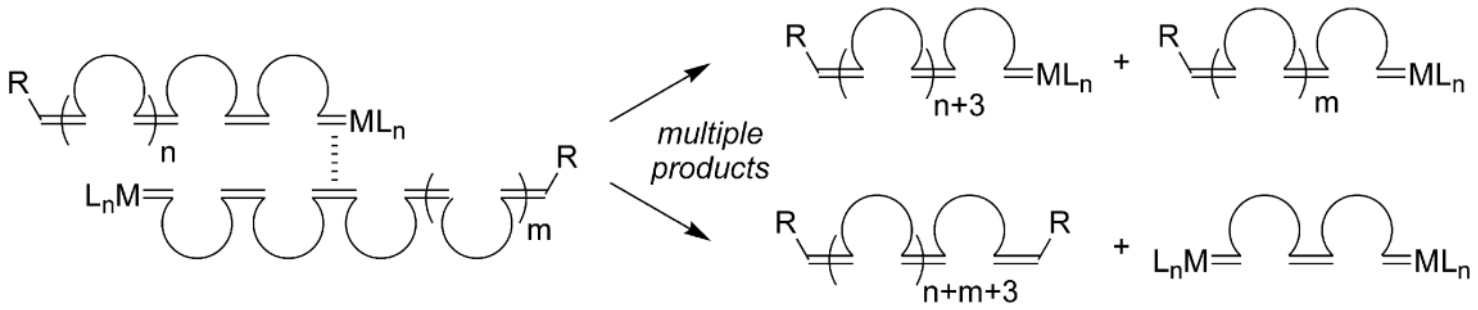


Hoveyda-Grubbs catalyst

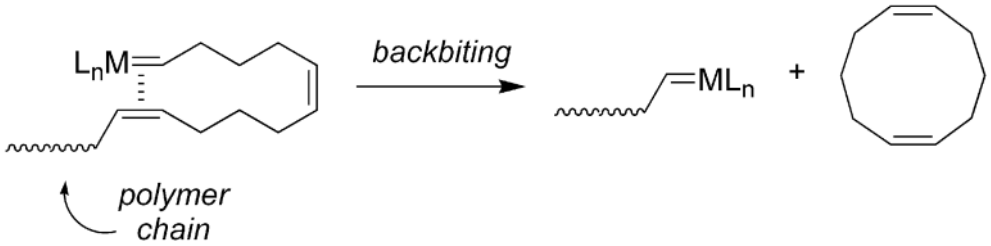
Grubbs catalysts generally have better functional-group tolerance than Schrock catalysts.

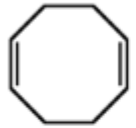
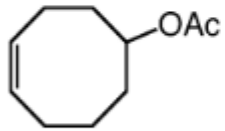
Chain Transfer in ROMP

Intermolecular Chain Transfer:



Intramolecular Chain Transfer:



Monomer	M_n	PDI
	112 400	2.3
	92 900	2.5
	10 700	2.1
	103 900	2.8
	79 300	3.2
	23 000	2.5

ROMP initiated by G2

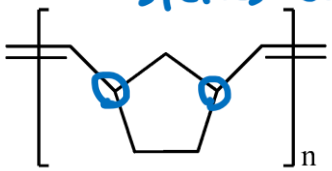
Secondary metathesis events lead to chain transfer, resulting in a broadening of molecular weight distribution. This is particularly problematic in the ROMP of low-strain cyclic olefins.

Bielawski, C. W.; Grubbs, R. H., *Angew. Chem. Int. Ed.* **2000,** *39*, 2903-2906.

Living ROMP

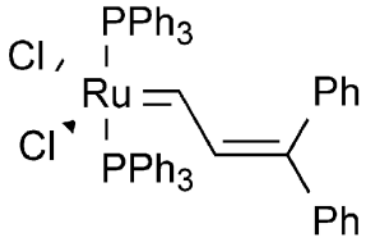
To achieve living ROMP, we need: 1) fast initiation and 2) no chain transfer or termination.

much more reactive than in-chain double bonds



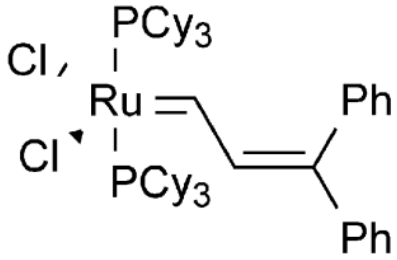
steric also disfavors secondary metathesis

Norbornene is a highly strained monomer (ring strain energy: 113.8 kJ/mol) widely used to study living ROMP.



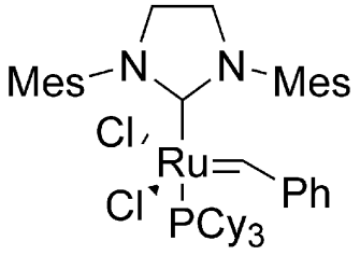
1992

Minimal secondary metathesis but activity is somewhat low



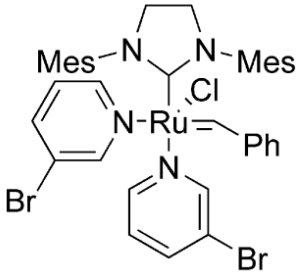
1993 (G1)

Very high activity leads to secondary metathesis (i.e., too active to achieve good control).



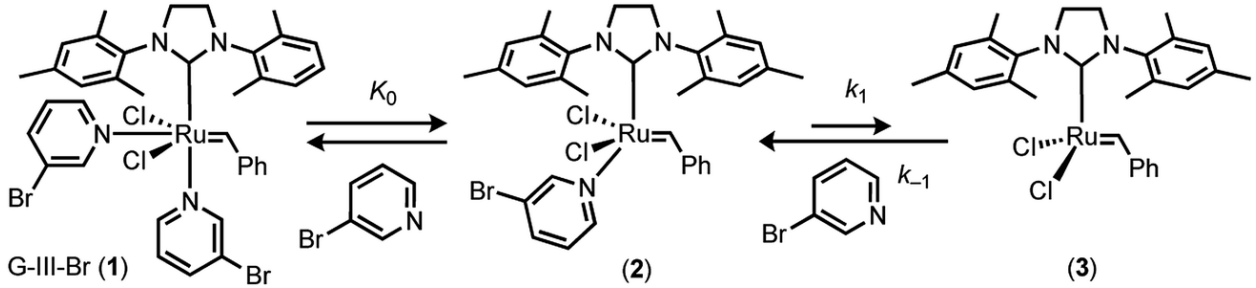
1999 (G2)

More stabilized intermediates, but broad dispersity due to slow initiation.



2001 (G3)

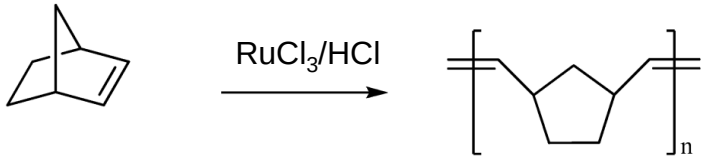
Fast initiation and living ROMP (dispersity below 1.1 for ROMP of norbornene).



Bielawski, C. W.; Grubbs, R. H., *Prog. Polym. Sci.* **2007,** *32*, 1-29.

Applications of ROMP Polymers

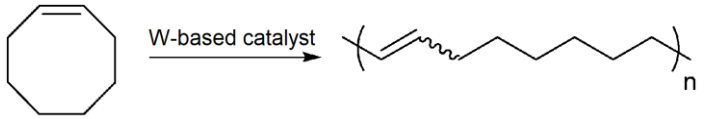
Polynorbornene (NORSOREX®)

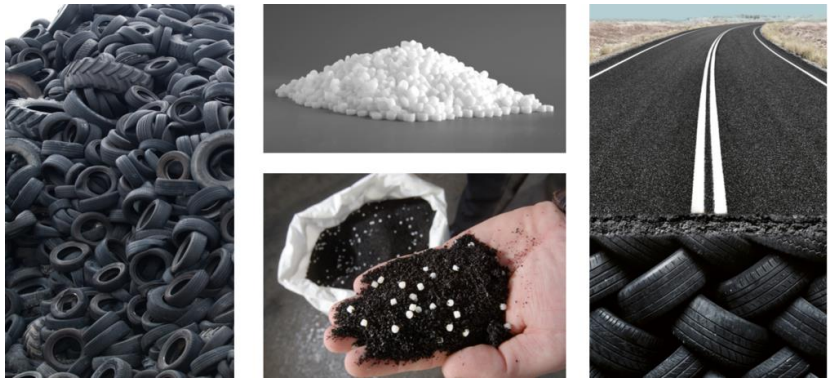


Automotive bumper Back protector

Antivibration and anti-impact materials

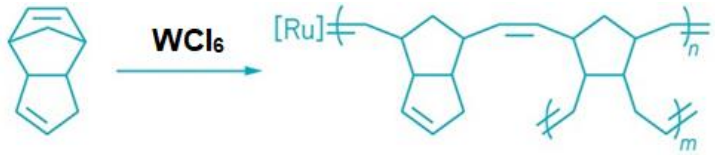
Poly(cyclooctene) (VESTENAMER®)





Additives that improve the processability of rubbers

Poly(dicyclopentadiene) (Metton®)

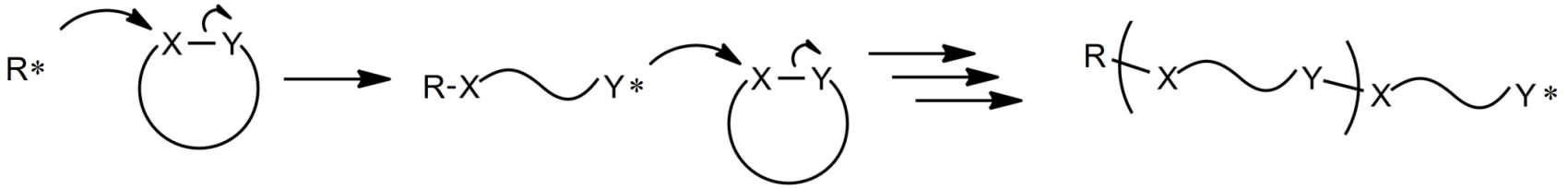


DCPD pDCPD

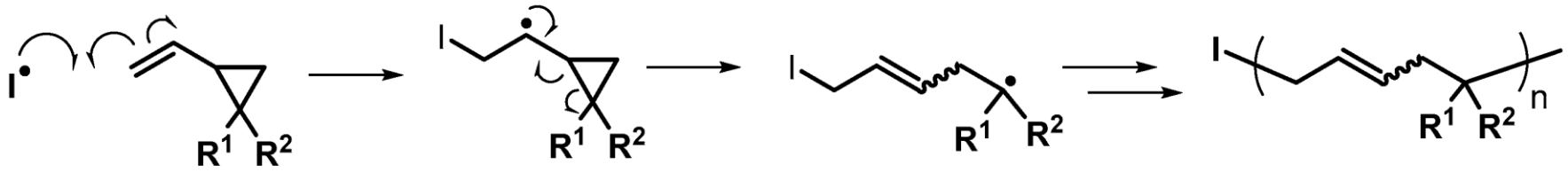
Superior mechanical properties

Although ROMP is a relatively new polymerization method, an increasing number of ROMP polymer products are being developed and are likely to appear on the market in the near future.

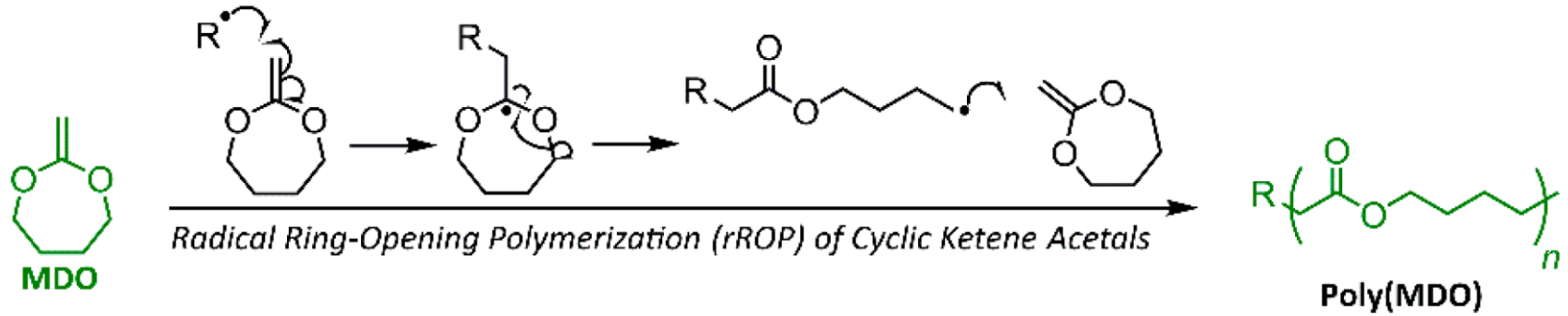
Radical Ring-Opening Polymerization



Can the propagating species be free radical in a ROP reaction?



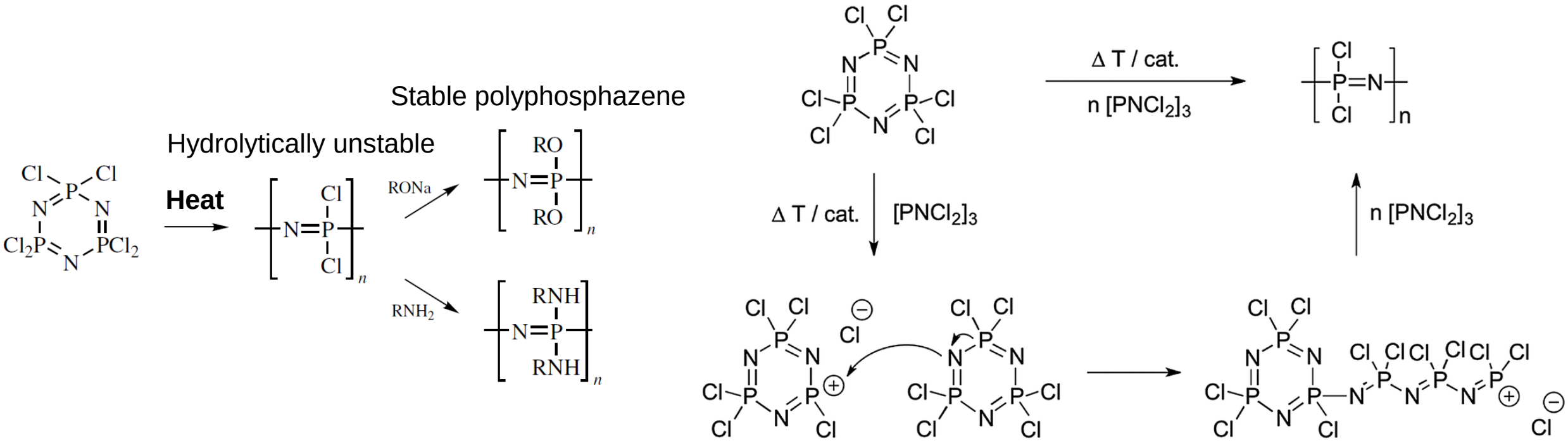
Polymerization of vinylcyclopropanes



Polymerization of cyclic vinyl acetals

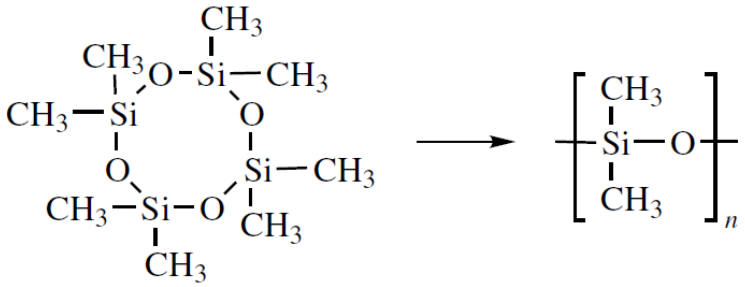
Tardy, A.; Nicolas, J.; Gigmes, D.; Lefay, C.; Guillaneuf, Y., *Chem. Rev.* **2017,** *117*, 1319.

Synthesis of Inorganic Polymers via ROP



- It is generally believed that the polymerization follows a cationic mechanism.
- The backbone of polyphosphazene is highly flexible. Thus, polyphosphazene was once commercialized as high-technology elastomers ("inorganic rubbers") for seals, O-rings, and dental devices. However, its use today remains quite limited.

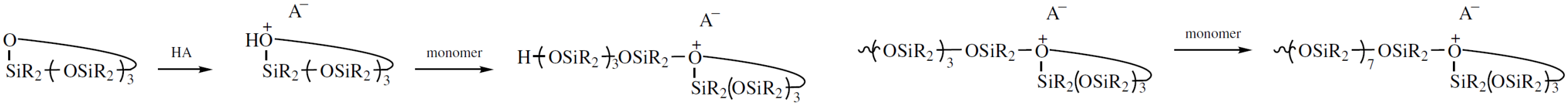
Synthesis of Inorganic Polymers via ROP



While polysiloxane (PDMS) can be synthesized via step-growth polymerization (Slide 28 in Lecture 4), higher-MW PDMS is synthesized by anionic or cationic ROP of cyclic siloxanes.

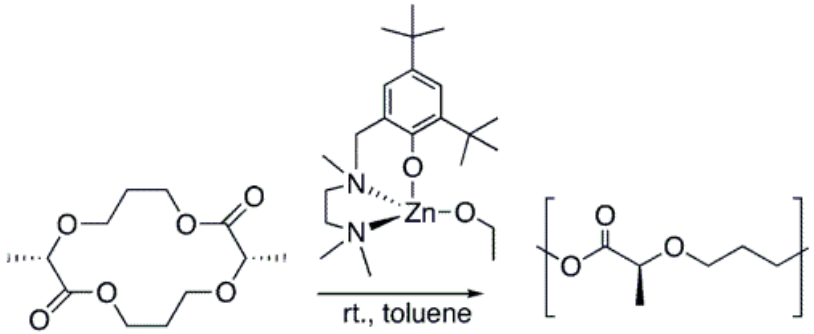
Anionic ROP (initiated by alkali metal hydroxides, alkyls, and alkoxides, etc.)

Cationic ROP (initiated by a variety of protonic and Lewis acids)



ΔH is nearly zero and ΔS is 6.7 J · mol^{-1} · K^{-1} (positive!). The driving force in this polymerization is the increase in entropy (disorder) on polymerization. PDMS backbone is highly flexible, which leads to greater degrees of freedom in the linear polymer compared to the cyclic monomer.

Additional Discussions on Enthalpy and Entropy



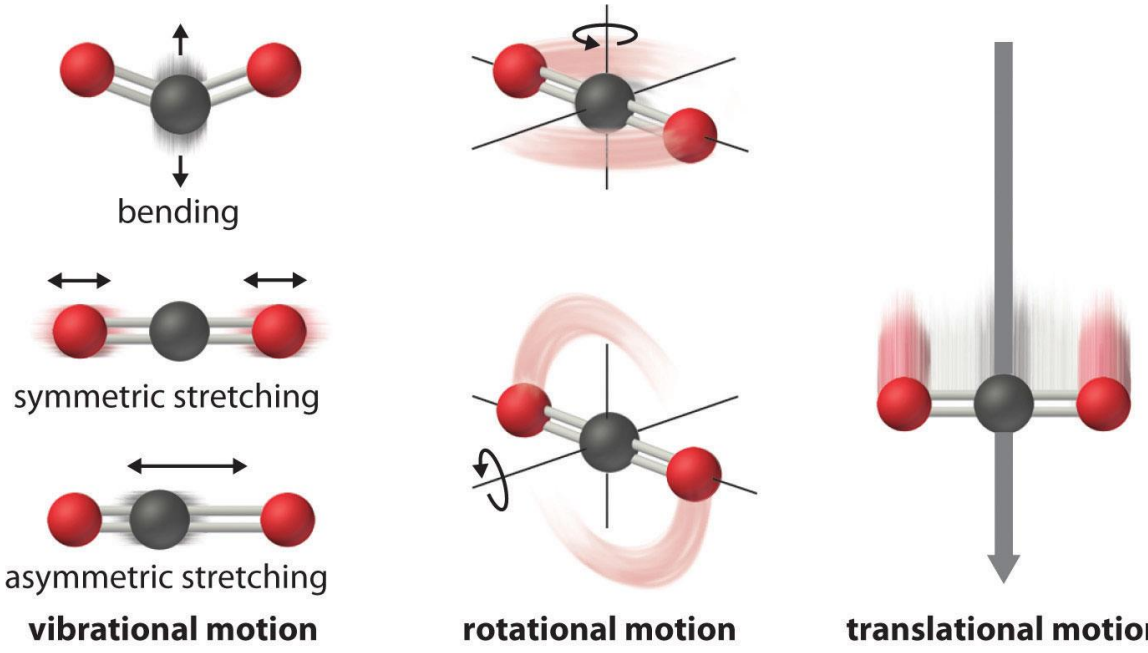
$\Delta H_p^\circ = 0.2 \pm 0.7\ \text{kJ} \cdot \text{mol}^{-1}$

$\Delta S_p^\circ = +16 \pm 2\ \text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$

$\Delta G = \Delta H_p^\circ - T\Delta S_p^\circ - RT\ln[M]$

$\approx 0 \quad < 0 \quad < 0$

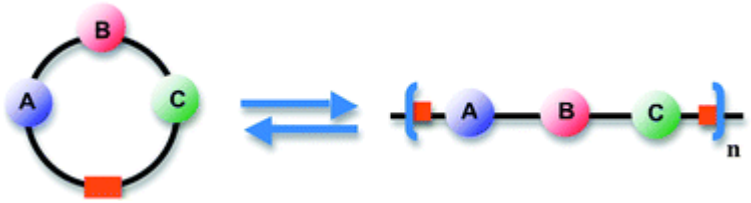
Molecular Motions



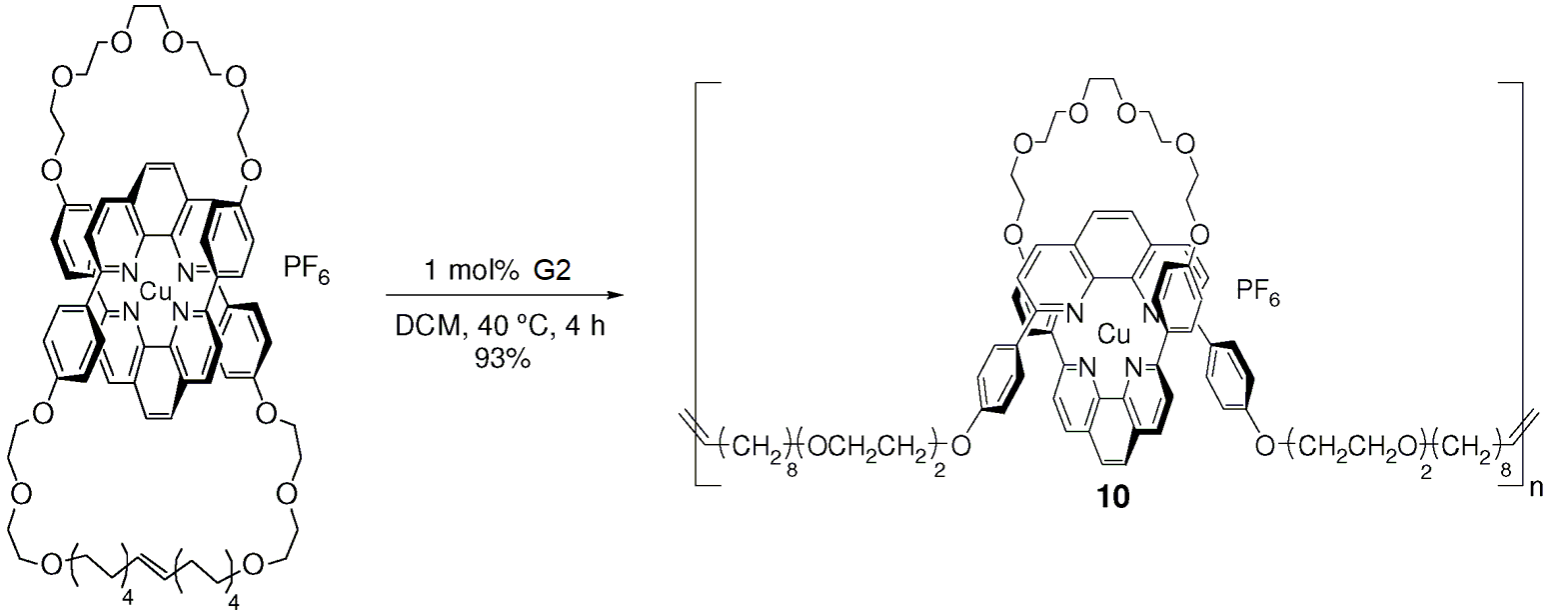
- For the polymerization of small cyclic compounds, the change in entropy is mainly dictated by translational entropy. Fixing small molecules on the polymer backbone greatly reduces their ability for translational motion, so entropy often decreases.
- For the polymerization of macrocyclic compounds, the change in entropy is mainly dictated by rotational/vibrational (i.e., conformational) entropy. Opening macrocycles to form linear chains increases conformational freedom, so entropy increases.

Zhang, D.; Xu, J.; Alcazar-Roman, L.; Greenman, L.; Cramer, C. J.; Hillmyer, M. A.; Tolman, W. B., *Macromolecules* **2004,** *37*, 5274-5281.

Entropy-Driven Ring-Opening Polymerization



- A large monomer concentration (5 M solutions or even neat) is needed to drive the ring-chain equilibrium.
- Dispersity is often high (close to 2.0).
- A good method for making main-chain functionalized polymers.



Kang, S.; Berkshire, B. M.; Xue, Z.; Gupta, M.; Layode, C.; May, P. A.; Mayer, M. F., *J. Am. Chem. Soc.* **2008,** *130*, 15246-15247.
Strandman, S.; Gautrot, J. E.; Zhu, X. X., *Polym. Chem.* **2011,** *2*, 791-799.