TECHNOLOGY TUTORIAL

The Chemistry of Norbornene Monomers and Polymers and Products and Application Areas

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Overview

- What is Norbornene?
- What are Functionalized Norbornene Monomers?
- How are Norbornenes Polymerized?
- Promerus Proprietary Catalysts
- Customization of Polynorbornene Polymers
- Products and Application Areas

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Promerus LLC is a Leader in Polycyclic Olefins

- We have 25+ years of Polynorbornene R&D and commercialization experience
- Our research and development efforts include:
  - ✓ Catalysis Research
  - ✓ Monomer Synthesis and Production
  - ✓ Polymerization Activities
  - ✓ Formulation Development
  - ✓ Application Validation
- We deliver a unique platform of materials for electronics packaging and other applications

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What Is Norbornene?

Norbornene is a bicyclic olefin.

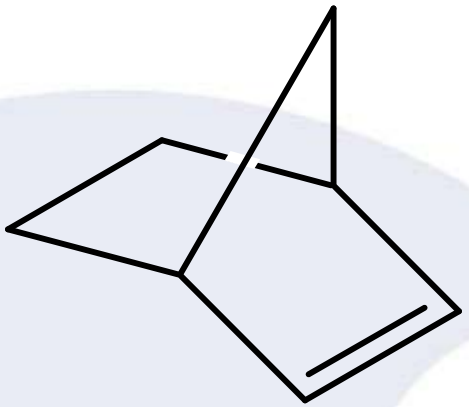
Norbornene possesses ring strain, so the molecule contains a highly reactive double bond.

Norbornene is manufactured via the Diels-Alder reaction of cyclopentadiene and ethylene.

Norbornene is a colorless substance that melts at 46°C.

Norbornene finds use in many different applications:

- ✓ Cyclic Olefin Copolymers (COC)
- ✓ Pharmaceutical intermediates
- ✓ Pesticide Compounds
- ✓ Specialty Fragrances
- ✓ General Organic Synthesis



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What are Functionalized Norbornenes?

Functionalized norbornene monomers are typically prepared via either high or low temperature Diels-Alder-reactions, and via derivatization.

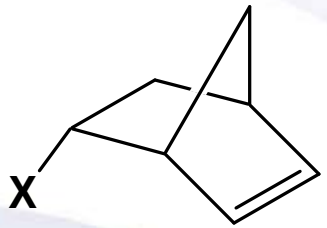
High purity, functionalized norbornenes can be as reactive as norbornene.

Functionalized norbornene molecules exist as two isomers: endo (major) and exo (minor).

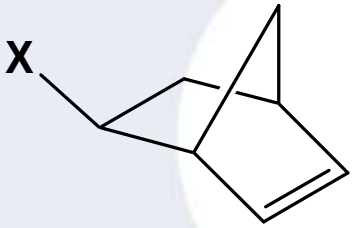
Many high purity, functionalized norbornenes are liquids.

Functionalized norbornenes contain many different types of reactive and non-reactive groups. Example substituents include:

- ✓ Acetate (OC(O)R)
- ✓ Alcohol (OH)
- ✓ Alkyl (R)
- ✓ Aldehyde (C(O)H)
- ✓ Anhydride (RC(O)O(CO)R)
- ✓ Epoxide ($CH_2C(O)CH$)
- ✓ Ester (CO_2R)
- ✓ Ether (OR)
- ✓ Ketone (C(O)R)
- ✓ Nitrile (C≡N)
- ✓ Silyl Ether ($Si(OR)_3$)
- ✓ Phenyl (Ar)



endo isomer



exo isomer

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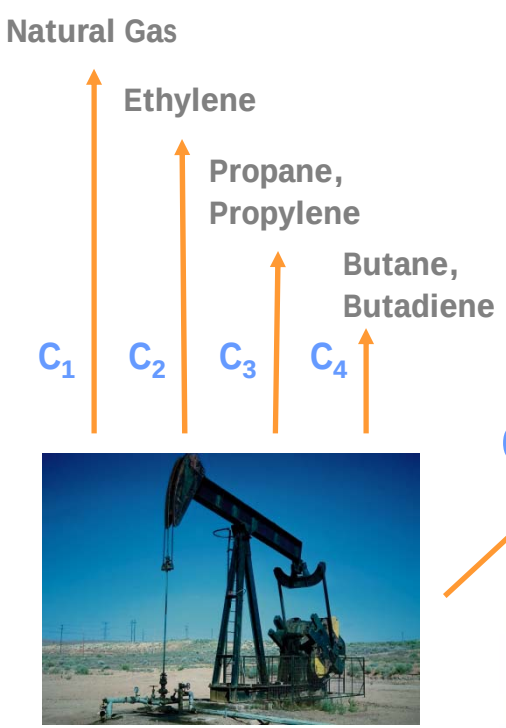
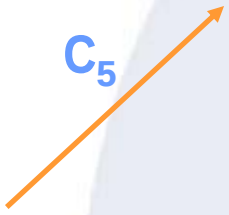
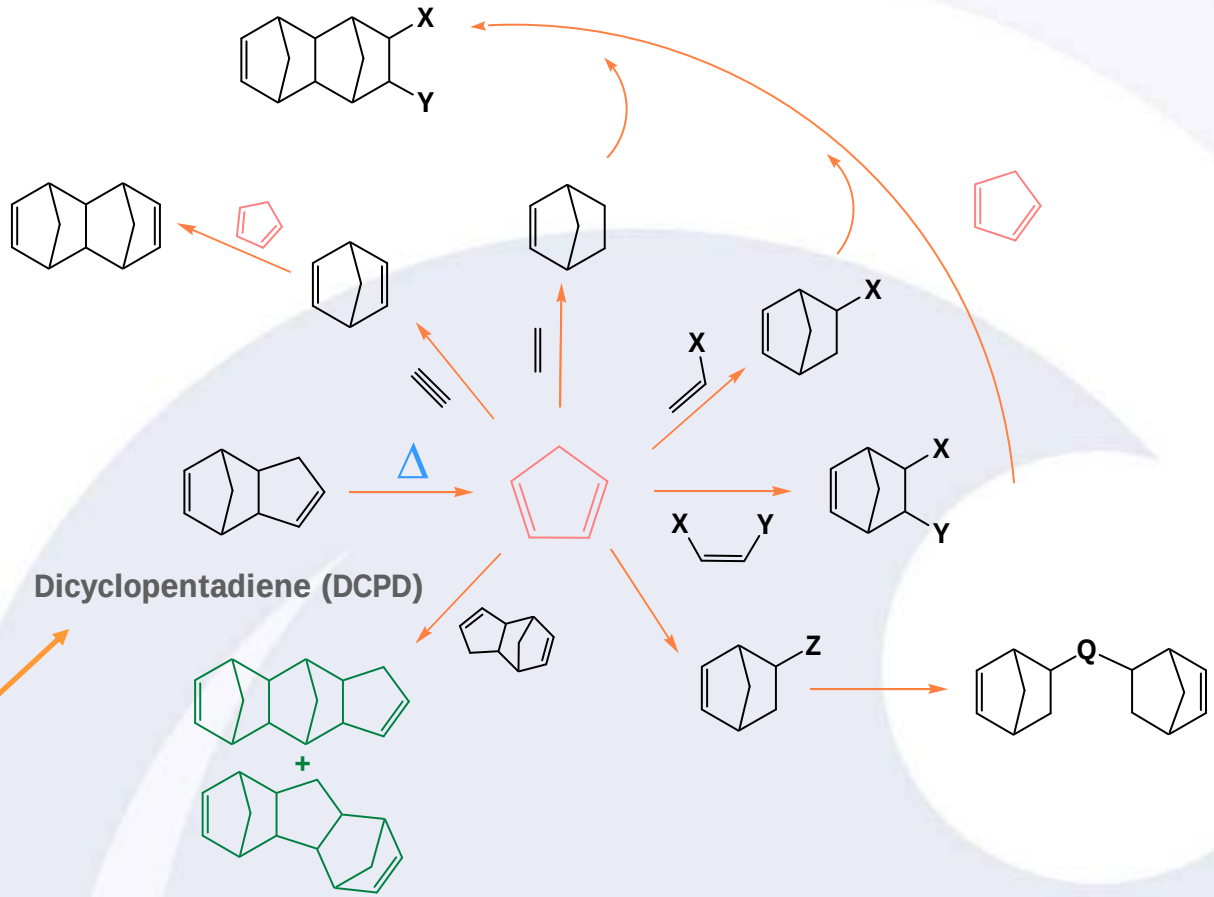
Diels-Alder Chemistry is Used to Prepare Norbornene Monomers







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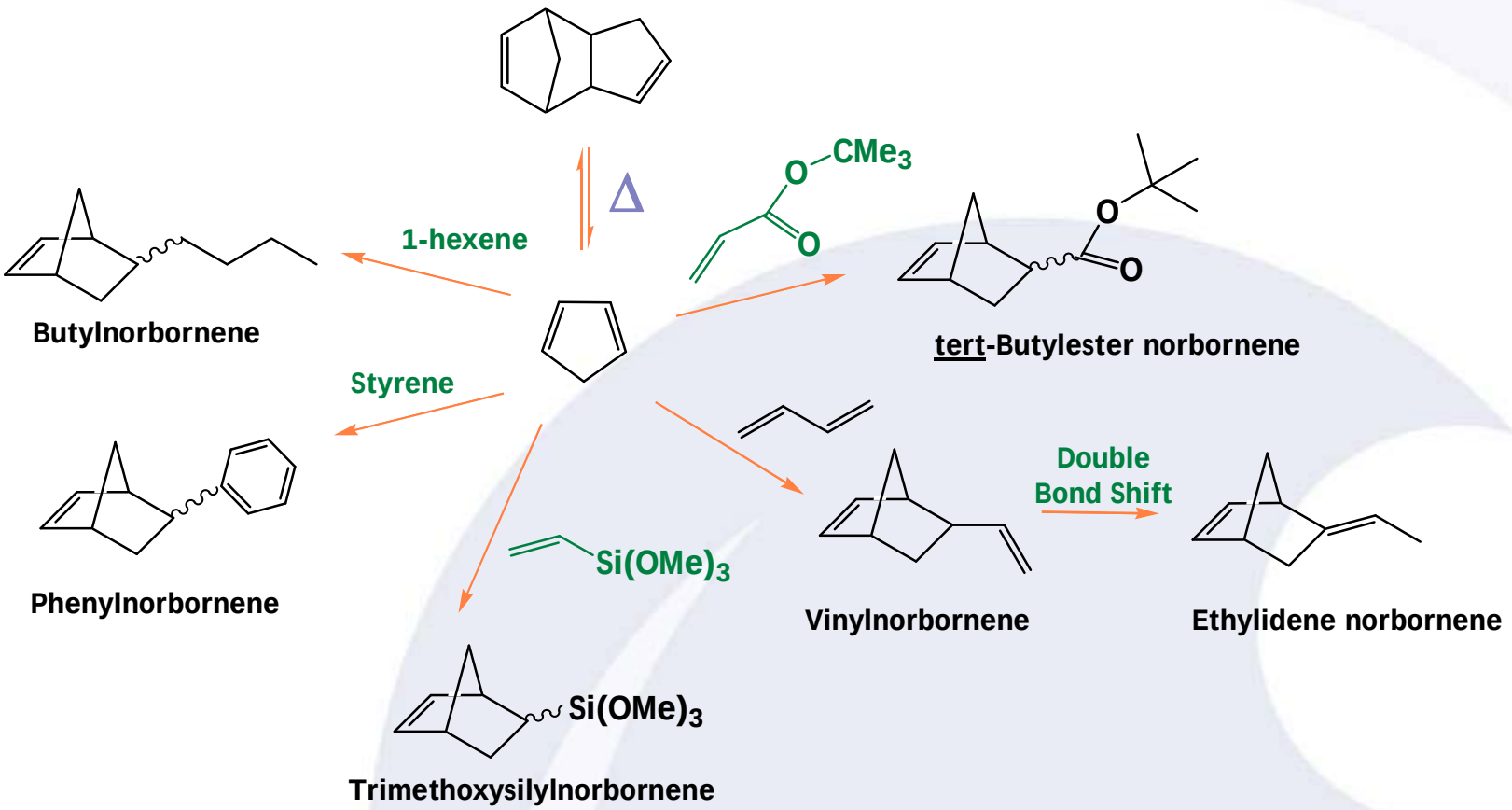
Norbornene Derivatives - Examples



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One Key to our Success is our Monomers

- High Purity
- Ease of Handling
- Multitude of Polycyclic Olefinic Building Blocks
- Huge Variety of Functional Groups
- Crosslinking Monomers
- Ring Strain Drives Polymerization

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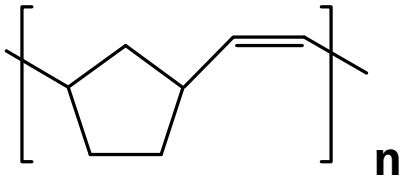
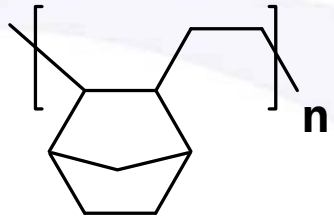
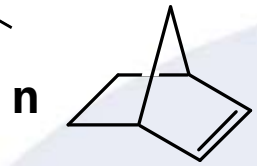
How is Norbornene Polymerized?

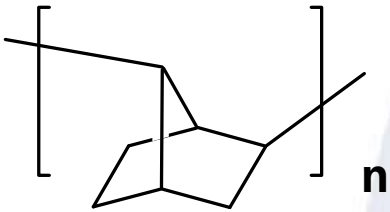


Ring-Opening Metathesis Polymerization (ROMP)

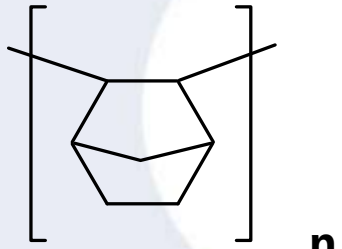


Ethylene Norbornene Co-Polymerization





Radical or Cationic



Vinyl- or Addition-Polymerization

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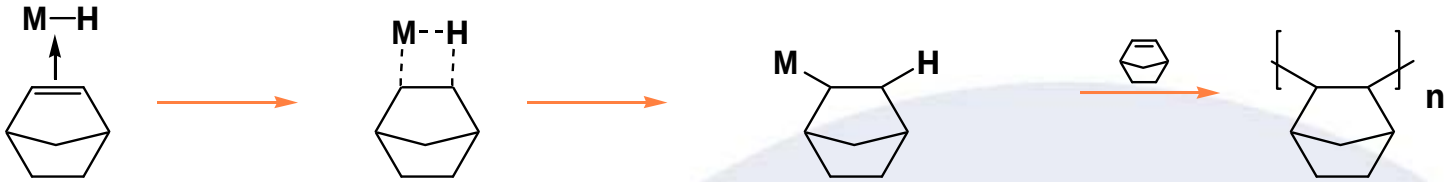
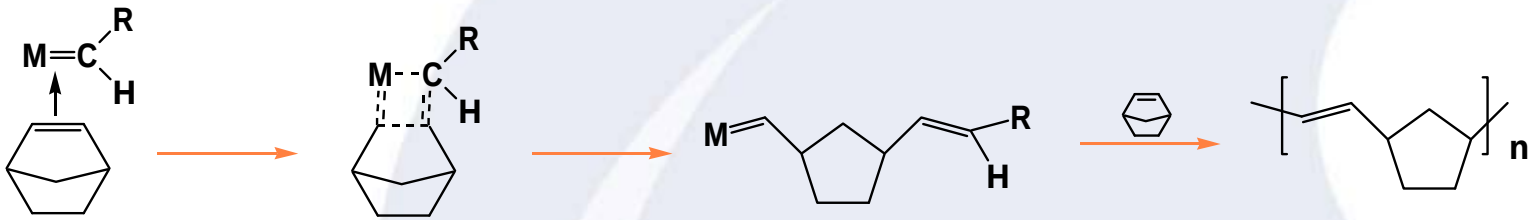
AP and ROMP Catalysts Yield Different Polymers

Addition Polymerization (AP) - Saturated



Ring-Opening Metathesis Polymerization (ROMP) - Unsaturated



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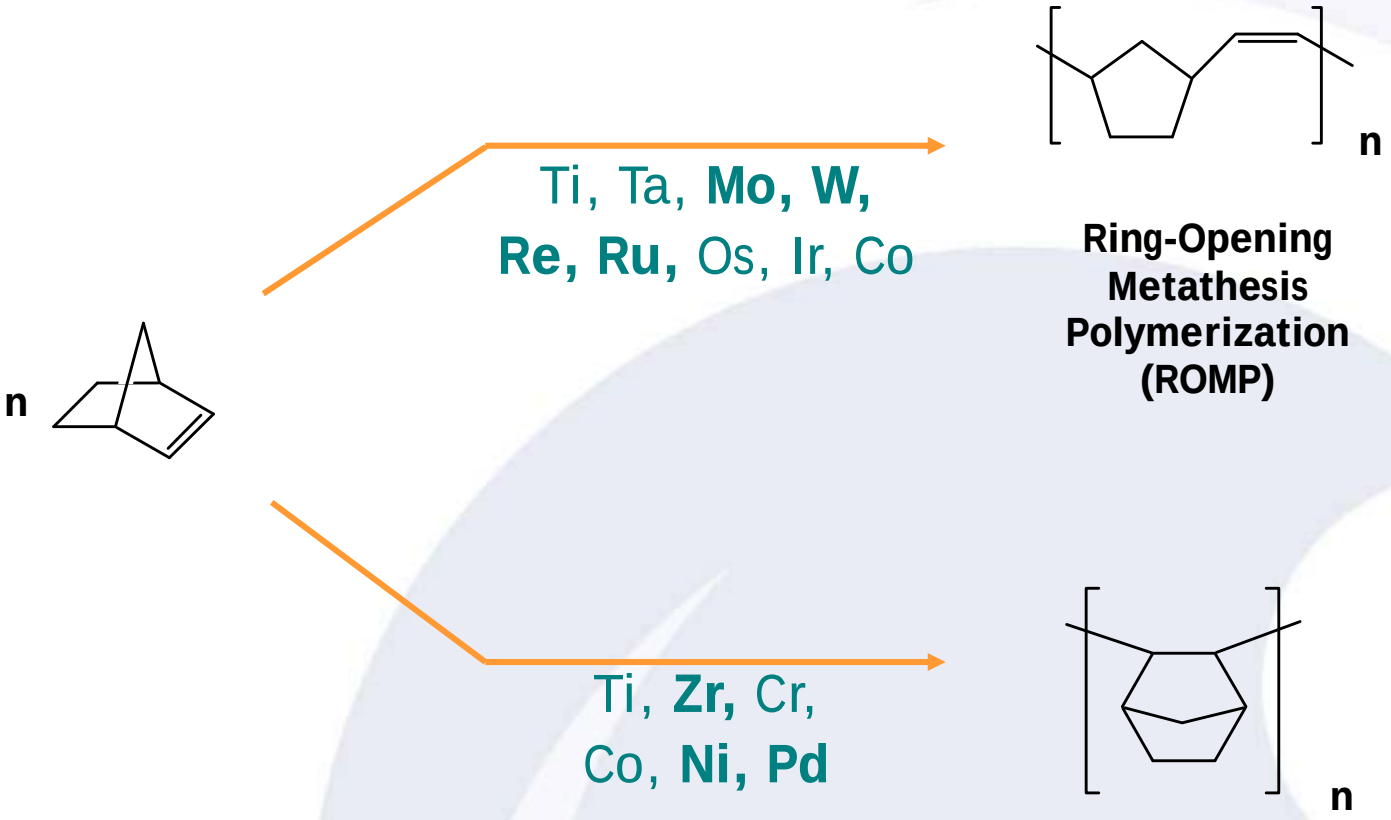
Several Transition Metal Initiators Can Be Used to Polymerize Norbornene



Predominant Transition Metals Employed in Bold

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Our Catalysts have Many Benefits

- High Activity, Single Component
- Low Residue in Purified Polymer
- Well-controlled Molecular Weight
- Functional Group Tolerance, e.g.,
  - ✓ Alkyl
  - ✓ Aryl
  - ✓ Ester
  - ✓ Epoxide
  - ✓ Ether
  - ✓ Silyl ether
  - ✓ Carboxylic Acid
  - ✓ Alcohol

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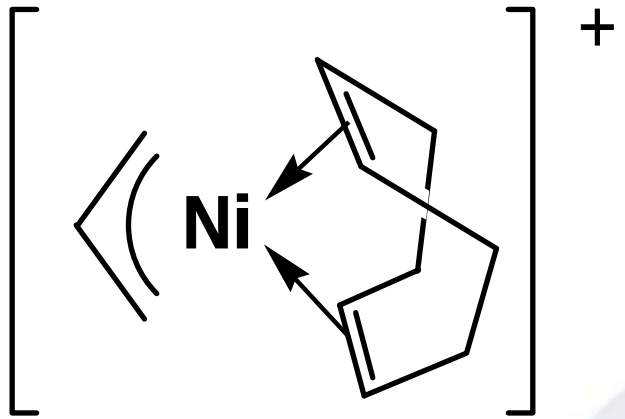
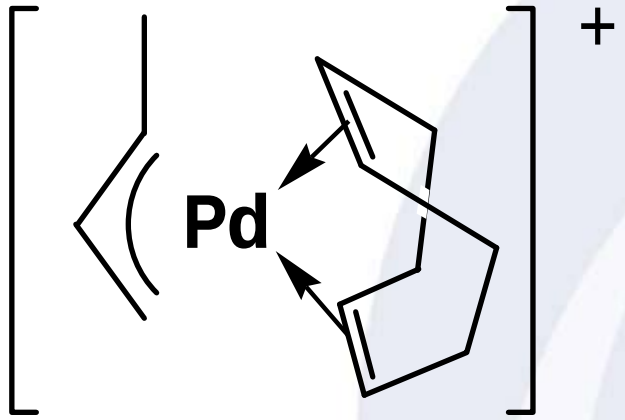
Some of our Catalysts are Well-defined Initiator Cationic Species





- Hydrocarbyl (or Hydride) Initiating Site
- "Naked" Cationic Metal Center
- Nickel and Palladium are Most Active
- Weakly Coordinating Anion
  - ✓ BF_4^-
  - ✓ PF_6^-
  - ✓ $B(C_6F_5)_4^-$

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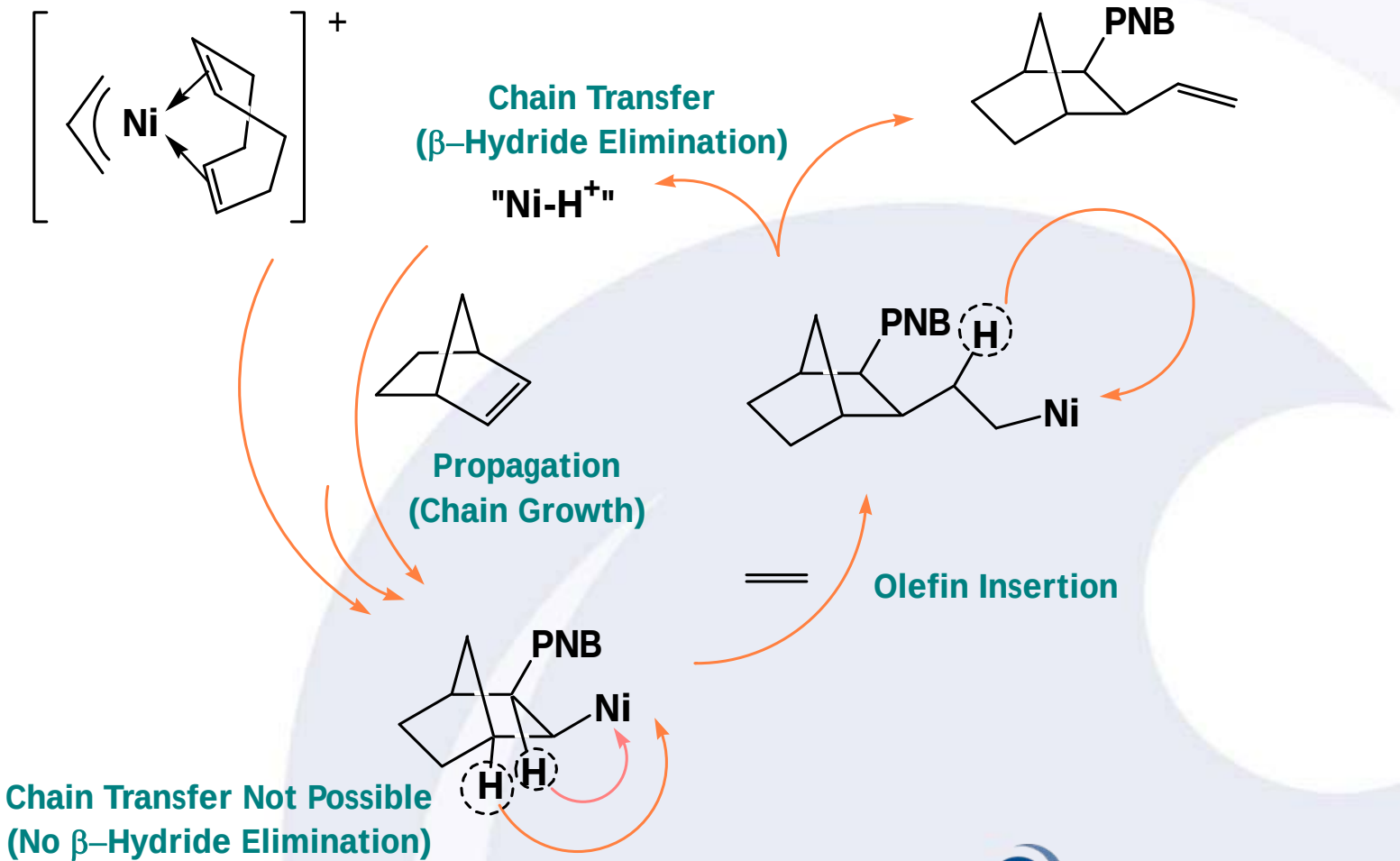
We Can Achieve Molecular Weight Control Via Chain Transfer



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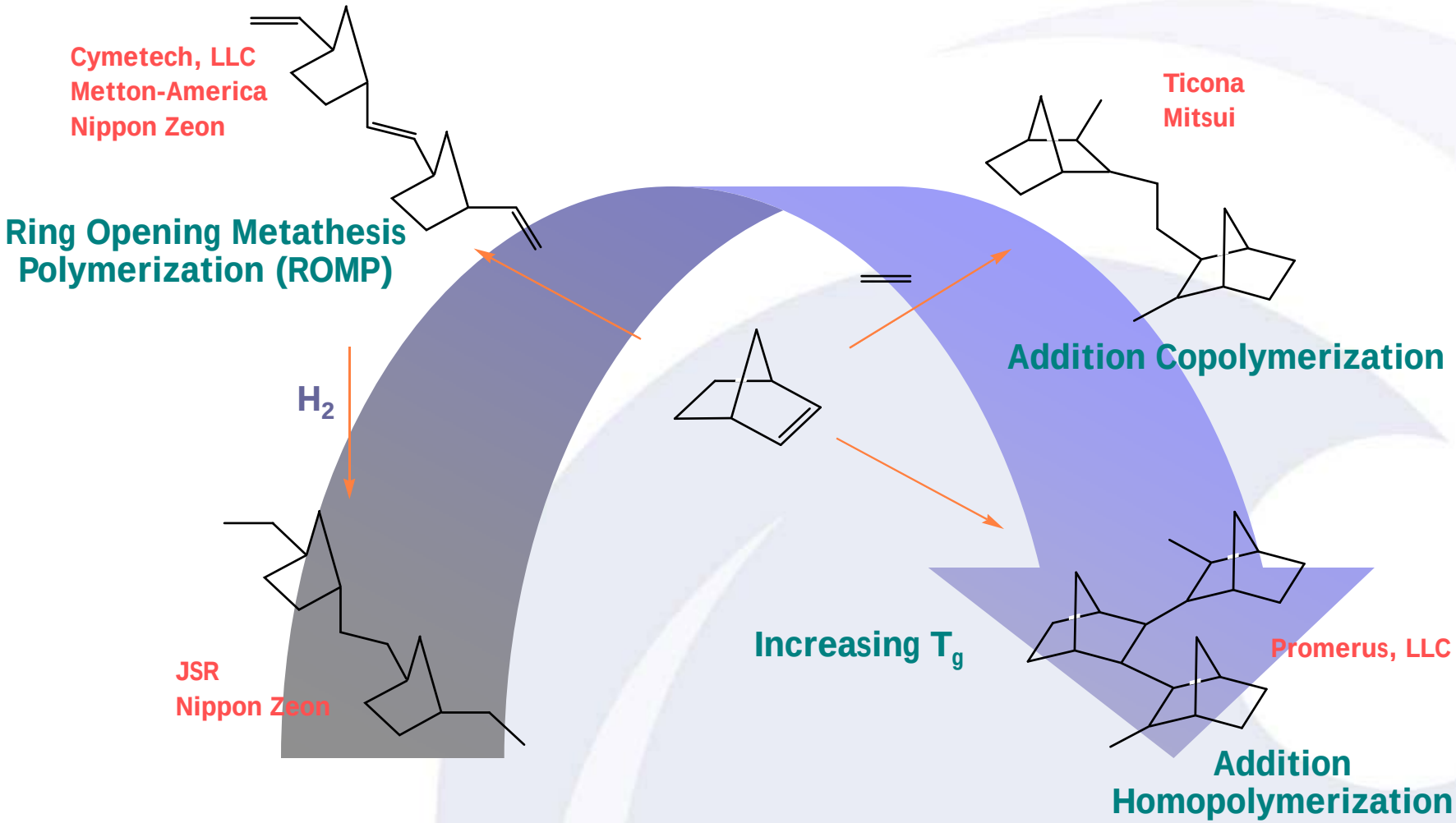
Promerus Polymers Have High T_g



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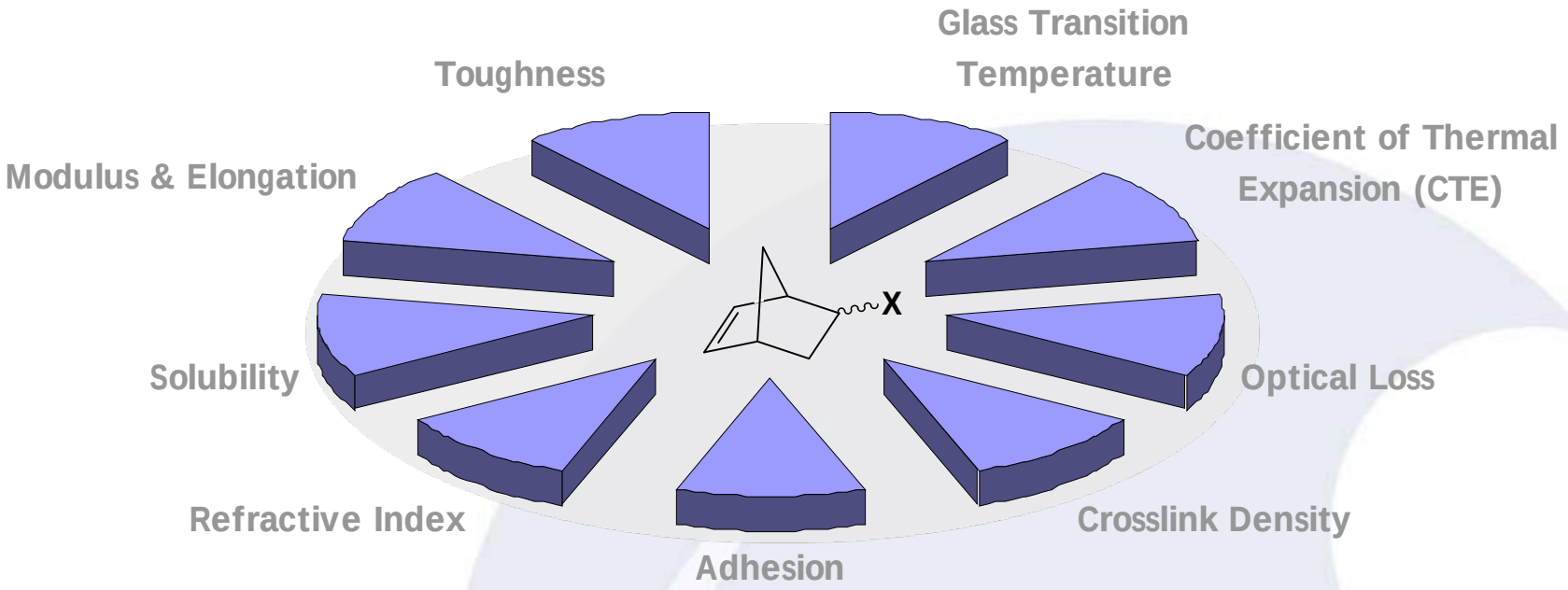
Polymer Properties Are Controlled by Changing the Functional Group



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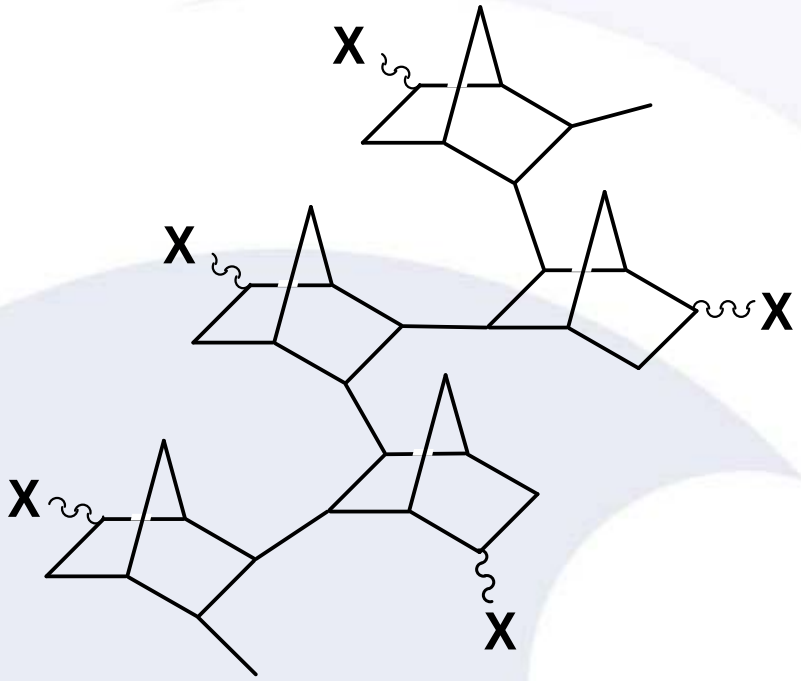
Why Use Promerus Polycyclic Olefin Polymers?

Amorphous Polyolefin

- Wide Spectral Window
- Low Moisture Absorption
- Low Dielectric Constant
- Chemical Resistance
- Low Birefringence
- Low Dielectric Loss
- High Breakdown Voltage



Rigid Polycyclic Backbone

- High T_g

Tailoring Polymer via Functional Group (X)

- Adhesion
- Refractive Index
- Latent Reactivity

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Promerus Materials Can Be Processed in Many Ways

Solution

- Spin Coating
- Solvent Casting

Post Treatment

- Photodefinable
- Latent Crosslinking
- Thermal Decomposition
- Surface Property Enhancement

Mass Polymerization

- Casting
- Resin Transfer Molding (RTM)
- Reaction Injection Molding (RIM)
- Screen-Printing
- Thixotropic Materials
- Composites

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Promerus Materials Are Useful in Many Applications

- Avatrel® Dielectric Polymers
  - ✓ For Electronic Packaging and Redistribution Layers
- Unity® Sacrificial Materials
  - ✓ For MEMS WLP, Protective Coatings and Temporary Wafer Bonding
- DUVCOR™ Photoresist Polymers
- Appear™ Optical Polymers
- Enestra® Optical Encapsulant
- Aprima® Adhesives

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